# SHORELINE OF PUERTO RICO

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SHORELINE OF PUERTO RICO

COASTAL ZONE MANAGEMENT PROGRAM
DEPARTMENT OF NATURAL RESOURCES
COMMONWEALTH OF PUERTO RICO

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This report on selected aspects of the shoreline of Puerto Rico is one of a series of reports prepared by this Department as part of the Coastal Management Program of Puerto Rico.

This report responds to the need for a better understanding of the complex interrelationships that exist in the near oceanographic regime of Puerto Rico.

The report focuses on different aspects of the beaches of Puerto Rico. The first concerns are the processes involved in beach development and the development of the coastal and beaches of Puerto Rico in response to these processes. There is a broad description of the types of beach sands, processes of sand movement, and man's impact on the beach system.

Comments on this report are welcome in order that we may be able to continue to improve our understanding of the shoreline and to seek better ways to cope with the problems of coastal erosion and sediment transport.

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Secretary

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REGIONAL GEOLOGY

The geological history of the earth is read from clues left in the rock record (fig. 1). The fossilized remains of past life in sedimentary rocks and radioactive dates from igneous rocks allow us to derive a calendar of earth history. Geological evidence indicates that the earth was formed more than 4.5 billion years ago. In rocks of Cambrian age, formed more than 600 million years ago, we find preserved fossil remains of plant and animal life. These fossils and geophysical evidence indicate that in the past the arrangement of oceans and continents was greatly different from the present distribution.

During the Paleozoic, the land masses formed one supercontinent that began to break up at the beginning of the Mesozoic. Rifting along the line of the mid-Atlantic ridge and subsequent drifting apart of the continents led to the origin of the Atlantic Ocean. The internal forces causing this movement added new crustal material in the region of the mid-ocean ridge.

The history of Puerto Rico begins less than 200 million years ago. The Caribbean basin is a creation of Mesozoic time and no rocks older than Jurassic age have been found. During the drifting of continents and movements of the earth's crust, blocks of the crust act as discrete plates. The Caribbean region appears to have been formed as the North American and South American plates separated during their westward drift. This was accompanied by great outpourings of lava which formed the platform upon which the Caribbean islands were formed. The oldest rocks in Puerto Rico are igneous rocks bound together by volcanic flows.

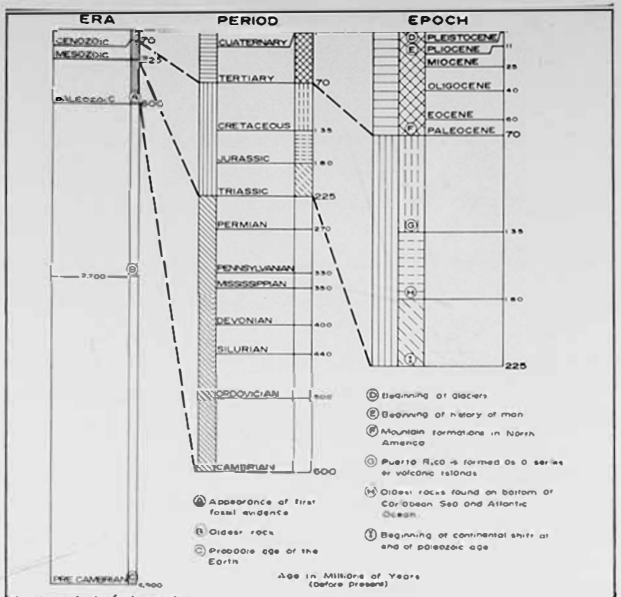



Fig. 1 geological time scale

The absolute age of the earth and history of past events is measured by the decay of radioactive elements. The ratio between decay products and parent radioactive materials is used to determine the elapsed time since the rock was formed. Sequences of change used include:

uranium 238 to lead 206
thorium 238 to lead 208
potassium 40 to argon 40
carbon 14 to nitrogen 14

The oldest known rocks in central Canada, Australia, and Russia date in age from 2.5 to 3.5 billion years in age. These are from ancient volcanic flows which poured out over an existing older earth crust. Cosmological evidence suggests that the age of origin of the earth is four and one half billion years ago.

In sedimentary rocks, fossils are our major means of correlation and interpretation of history. The succession of rock formations and fossils is used to build a geological history. This knowledge was used to divide and name divisions of earth history that are separated by world wide appearance of climate change, mountain building, and widespread plant and animal migrations. The major divisions are eras; these are subdivided into periods, and the divisions of the periods are epochs. This is a relative time scale and must be tied to the radioactive scale by correlation between sedimentary and igneous rocks.

No major fossil material is found in rocks older than the Cambrian (±600 million years ago) so that the record of plant and animal life is restricted to the last one eighth of the history of the earth.

To better understand the immensity of geological time, we might compare the history of the earth to a 24 hour clock and note the following events

| hrs min sec | |
|---|---|
| 00 | 4500 million years ago origin of the earth |
| 20:48 | 600 million years ago fossil record starts Cambrian |
| 22:36 | 200 million years ago Puerto Rico begins forming |
| 23:59:22 | 2 million years ago origin of man |

Puerto Rico was formed on the emerged crest of an elongated ridge that trends through Hispaniola, Puerto Rico, and the Virgin Islands. The central structure is a Cretaceous volcanic framework, flanked by thick mid-Tertiary sediments on the north and south and bounded by the seismically active Puerto Rico Trench and the Anegada Trough. An initial lowland was built up by explosive volcanic activity which was partially underwater eruptions. The core of Cretaceous to Tertiary volcanics and volcanic sediments are two-thirds of the present land area of Puerto Rico.

During the Cretaceous, Puerto Rico was probably a chain of volcanic islands. Pyroclastic sediments from volcanic activity and marine carbonate deposition built on the original platform. Oscillations of the land and alternation of volcanic activity with normal marine sedimentation is recorded in the rock record.

From the close of the Mesozoic through early Tertiary time, large segments of the earth's crust were subjected to intensive deformation by the Laramide orogeny. In Puerto Rico, the response to the compressive forces was extensive folding and volcanic activity. The Cenozoic rock sequences continued to be marine sediments alternating with igneous rocks.

The youngest rocks on the Island, Oligocene to Recent age, are mainly limestones and surficial sedimentary deposits of the coastal areas (fig. 2). These younger sediments were deposited during marine invasions over an irregular topography. The carbonate formations of the north and south coasts trend east-west and dip toward the sea. On the north coast, seismic records show that these formations extend twenty miles offshore and maintain a constant dip of six degrees and have a thickness of more than 1500 meters.

During the later history of the Island, dissection of the land mass and sagging resulted in an irregular coast with varying depositional areas. Gravels, sands, and silts were being formed from land erosion, while coral reefs added marine limestones on the shallow shelf. As deposition and subsidence continued, the relief was smoothed and a more uniform sequence was deposited.

The southern limestones are of lesser areal extent than those on the north coast. East of Ponce, the carbonates are buried under thick sediment fans from the mountains that form a broad alluvial plain (fig. 3). A submerged platform more than fifty kilometers long and fifteen kilometers wide borders the south and west coast (fig. 4). This platform has more than 600 meters of limestone sediments.

Fig. 2 coastal limestone
The Miocene limestones at Borinquen airport form 50 meter high cliffs.

Fig. 3 alluvial fan deposits
At Central Machete on the south coast, material eroded and transported from the mountains forms a broad alluvial plain along the coast.

Fig. 4 limestone platform
The marine shelf at La Parguera is eight to ten kilometers wide with an average depth of 18-20 meters. It is underlain by Cretaceous limestones and covered with shoal reefs and carbonate sand deposits.

Four major glaciations occurred during Pleistocene time (fig. 5). Each of these glaciations caused a lowering of sea level of about 100 meters. The interglacial periods witnessed a retreat of ice and a rise of sea level. There has been an overall lowering of sea level since the beginning of Pleistocene time as water has been permanently trapped in the higher latitudes. The final glaciation, the Wisconsin, had the most profound effect on the present coastal features, and the rising sea level following glacial retreat is one of the major factors affecting our present coastal pattern and beaches.

The Miocene limestones of Puerto Rico are overlain by Pleistocene to recent alluvial and coastal sediments. Along the north coast, the alluvial deposits form a reworked blanket of sand and sandy silts inside the karst topography and the river valleys. Coastal deposits including cemented sand dunes (fig. 6) (eolianites), modern sand dunes (fig. 7), lagoon and swamp sediments, beach rock (fig. 8), and beach sands are distributed along the coast from Arecibo to the Rio Grande de Loiza.

On the south coast, the alluvial deposits are distributed along the present rivers, or form a series of overlapping alluvial fans which coalesce into broad alluvial plains. Coastal deposits of beach sand and gravels, swamp and lagoons (fig. 9) sediments, and coral reefs (fig.10) fringe the coast. On the west and east coasts of Puerto Rico, the surficial deposits fill valleys which are generally locations of transcurrent faults.(fig. 11).

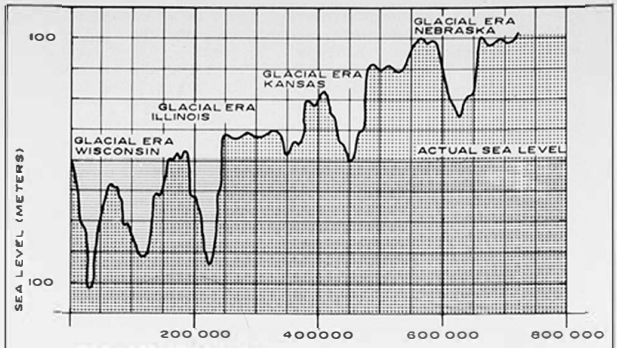



Fig. 5 Glacial fluctuations of sea level
As the glaciers grew and advanced over land areas, the precipitation being added to the ice mass was supplied by removal of seawater from the oceans. This resulted in a loss of volume of available seawater and subsequent lowering of sea level in relation to the land. Each glacial episode is named for the maximum geographic advance of the ice sheets over North America.

Fig. 6 eolianite (fossil sand dune)
These cemented sand dunes of the north coast were formed at an earlier time as dunes and were subsequently cemented.

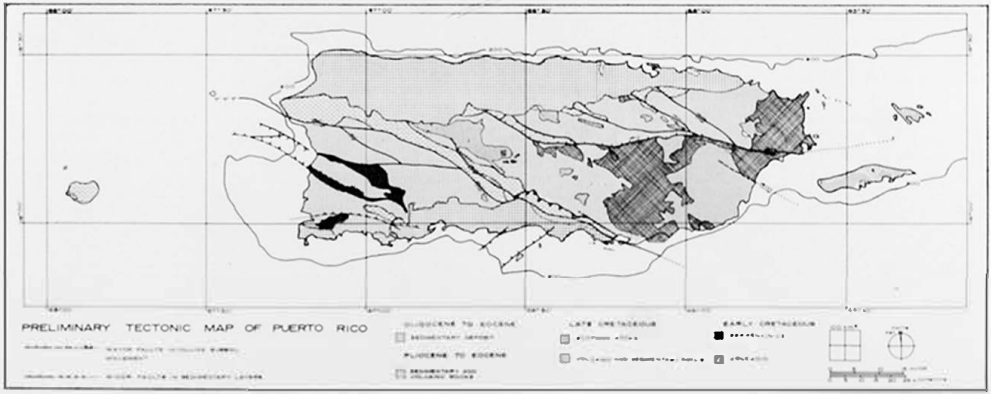
Fig. 7 coastal sand dunes
The sand dunes north and east of Borinquen airport form a reservoir of sand for beach nourishment. They have been exploited for commercial sand and offer little protection to the shore against hurricane associated waves.

Fig. 8 beachrock
The cemented sands at Cibuco, on the north coast, mark former shoreline positions. Many of the north coast beachrock exposures are less than 100 years ago and were cemented while underlying the beach system. Their exposure indicates conditions of erosion.

Fig. 9 mangrove swamps
La Parguera forest on the south coast is one of the major mangrove coasts. The growth of the mangrove and trapping of sediments has resulted in accretion of land area to the Island.

Fig. 10 coral reefs
There are numerous corals forming a fringing reef at Punta Guaniquilla on the west coast. The sediments are coral fragments, mollusk shells, foraminifera, echinoid fragments, and other shell material including coralline algae.

Fig. 11 tectonic map of Puerto Rico
The oldest rocks exposed in Puerto Rico are Cretaceous age. The rock types are principally volcanic and intrusive igneous rocks, and limestones. Structural trends and the major faults are oriented roughly east-west. Major faults such as the Great Southern Puerto Rico Fault extend offshore both to the east and the west. The northern coastline and about half of the southern coast are composed of sedimentary Quaternary deposits. The west, southeast, and east coasts are dominantly Tertiary to Cretaceous volcanic and intrusive igneous rocks.



The narrow submerged shelf surrounding Puerto Rico was cut during the period of Wisconsin glaciation. The low point of sea withdrawal was some 15,000 years before present time, and sea level was more than 120 meters below the present level. There has been a fairly rapid rise, marked by interruptions, until the sea approached its present level 5,000 years ago. The interruptions in glacial retreat and concomittant sea level rise allowed the development of marine terraces and exerted some control on shelf depth and features (fig. 12). Many of the shelf sediments were formed during this period of sea level rise. The present beach systems have developed during the last 5,000 years, since the sea approached its present level. Relict sand and beach lines, formed earlier, lie on the shelf itself. A continuing slow rise of sea level and minor fluctuations of uplift or sinking of the coastal regions have a profound effect on the beach system.

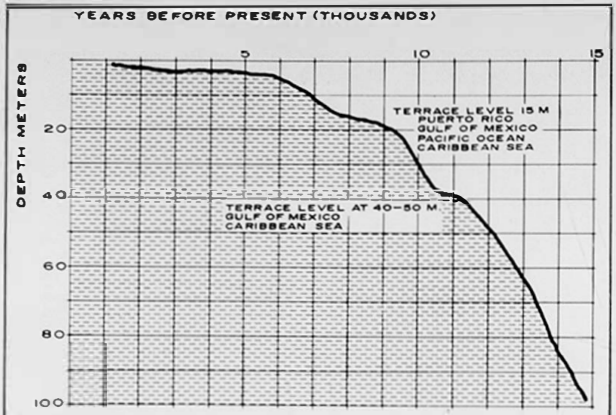



Fig. 12 sea level curve
The return of sea level after the Wisconsin glaciation was rapid until about 7000 years ago. By that time sea level was within five to ten meters of the present level and there was a gradual and decreasing rate of rise. Still-stands in sea level rise allowed the development of marine terraces that are marked by coral growth. These are observed in many parts of the Caribbean, Gulf of Mexico and the Pacific. The most prominent terrace levels are at 15 meters and 40 to 50 meters.

## COASTAL DEVELOPMENT AND CLASSIFICATION

Coastal forms and features vary considerably in Puerto Rico since the coast is acted upon by many processes and the nature of the materials forming the coast vary. We can group coasts into three significant types:

rocky shorelines with cliffs and headlands (fig. 13)
sand and cobble beaches (fig. 14)
mangrove - mud flat - marsh grass coast (fig. 15)

Classification schemes may seem tedious, but they allow us to compare and contrast what we see and to form conclusions about the origin of the various coastal types. In the following modification of the classification scheme devised by Shepard, there is a basic division into primary coasts that have not been significantly affected by marine processes and secondary coasts that have been shaped by marine processes. The secondary or mature coastal type is not only dependent on time for the modification, but also on the type of materials forming the coast, available physical energies, and the ecosystem.

The coast is a meeting place of energies. Rivers, volcanoes, wind, and earth movements expend energy in a seaward direction in eroding the land. Resistance to this erosion is dependent on the lithology and structure of the rocks. Waves, currents, and marine organisms expend energy shoreward and contribute to the development of the coastal configuration. The effect of these forces can be evaluated more easily with the aid of this coastal classification system.

Rivers carry sediment to the sea where it is redistributed by marine processes. If the wave energies and currents cannot keep up with the supply, then deltas, bars, and other features will extend the coast seaward. Where marine forces are adequate, the sands are distributed across the shelf. Strong marine forces coupled with a low supply of sediment can result in erosion of the land area at a fairly rapid rate.

The rising sea level that accompanied the melting of glaciers at the close of the Pleistocene had a profound effect on coastal configuration. Where deposition could not keep pace with the rising waters, many Pleistocene features were drowned. Drowned river valley coasts are classed as ria coasts and drowned glacial valleys form fiord coasts. A combination of rapid submergence, relatively hard rock coast, and low sediment supply leads to the development of these coasts.

In many coastal regions volcanic activity is important and the coast may be shaped by lava flowing into the sea or by the building of volcanic cones.

The proliferation of particular plants and animals may dominate coastal and nearshore environments, and in the tropical regions coasts built by marine organisms are especially common. These

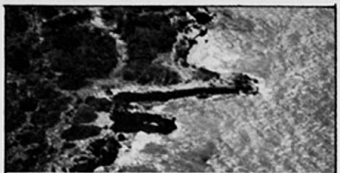


Fig. 13 rocky shoreline
The southwest coast of Puerto Rico.

Fig. 14 sandy beach
Añasco Beach.

Fig. 15 mangrove shoreline
Puerto Real on the west coast.

are dominantly coral reef and mangrove coasts. In higher latitudes, the mangrove coast is replaced by marsh grasses

A geological factor which does not build coasts, but strongly determines how external forces shape them is lithology. Some rocks are less resistant to chemical solution than physical forces, or vice versa. A rock's susceptibility to physical and chemical erosion is related to its composition, degree of cementation, structure, and fracture patterns. Thus, under some conditions, we may have a primary coast because of lack of rock erosion, while the same physical forces would cause a secondary coast given different underlying rock formations.

COASTAL CLASSIFICATION

PRIMARY

- A. land erosion
  - 1. ria-submerged river valley
  - 2. glacial valley
    - a. fiord
    - b. glacial trough
- B. subaerial deposition
  - 1. river
    - a. deltaic
    - b. compound delta
    - c. alluvial fan
  - 2. glacial
  - 3. wind
    - a. dune (fig. 16)
    - b. eolianite (fig. 17)
- C. volcanic
  - 1. lava flow
  - 2. tephra
- D. shaped by diastrophic movement
- E. ice

SECONDARY

- A. wave erosion
  - 1. straightened by waves (fig. 18)
  - 2. made irregular by waves (fig. 19)
- B. marine deposition
  - 1. barrier coasts (fig. 20)
  - 2. cuspate forelands
  - 3. beach plain (fig. 21)
  - 4. mud flat
  - 5. beach rock (fig. 22)
- C. built by organisms
  - 1. coral reefs (fig. 23)
  - 2. serpulid reefs
  - 3. oyster banks
  - 4. mangrove (fig. 24)
  - 5. marsh grass

Fig. 16 dune coast
Extensive sand dune area west of Isabela. Most of the dune sand has been removed.

Fig. 20 barrier coast
The barrier spit across the mouth of the Rio de la Plata is a type of barrier coast.

Fig. 17 eolianite coast
North coast, near Marchiquita.

Fig. 21 beach plain
Punta Tuna on the southeast coast is a broad beach plain resulting from marine deposition.

Fig. 18 straightened by waves
South coast near Arroyo. The cliff is cut into unconsolidated alluvium.

Fig. 22 beach rock
At Boquilla beach east of the Rio Manatí the shoreline between the eolianite outcrops is beachrock.

Fig. 19 made irregular by wave erosion
South coast, near Punta Verraco. Differences in the limestone formation, fractures and faults, and changes in wave energy have resulted in differential erosion of the coastline.

Fig. 23 coral reef
The fringing coral reef north of Fajardo forms the coastline. There is a narrow sandy beach behind the reef.

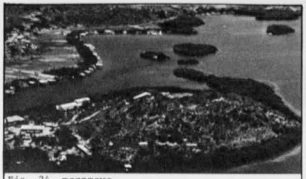


Fig. 24 mangrove
The shoreline at La Parguera is a narrow strip of mangrove. Immediately behind the shoreline there is a tidal flat.

Fig. 25 sandy beach
There is a low sloping foreshore, crest, berm, and backshore shown in this photograph.

| | | |
|---|---|---|
| boulder | | |
| | 256 | |
| cobble | 128 | |
| | 64 | |
| | 32 | |
| pebble | 16 | |
| | 8 | |
| | 4 | |
| | 2 | |
| | 1 | |
| sand | | .5 |
| | | .25 |
| | | .125 |
| | | .0625 |
| | | .03125 |
| silt | | .01562 |
| | | .00781 |
| | | .0039 |
| | | .002 |
| | | .00098 |
| clay | | .00049 |
| | | .00024 |
| colloid | | |

Fig. 28 Grain size classification
Particles larger than 2.0 mm are gravel, 0.063 to 2.0 mm grains are sand, 0.002 to 0.063 grains are silt, and particles smaller than 0.002 mm are clay size.

Fig. 26 recreation beach
Boqueron beach on the southwest coast is one of the public beaches supervised by the Public Parks and Recreation Administration.

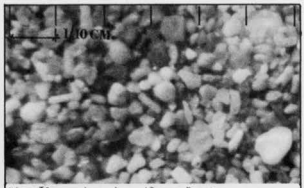


Fig. 29 sand grains, Añasco Beach
This macrophotograph of beach sand shows the size and variety of materials that may be found in a beach sand.

Fig. 27 sand extraction
In this area, just east of Isabela, sand was not only removed from the dunes, but apparently from the beach itself, leaving a major change in the coastline.

Fig. 30 beach gravel
This coarse rock gravel forms the beach at Las Ochenta.

## BEACHES

A beach is an unconsolidated shore of sand and gravel (fig. 25). This definition excludes muddy shores found in quiet water conditions and rocky shores where no appreciable amount of loose sediment exists. Beaches are unstable features geologically and may advance, retreat, or even disappear. They are of great economic importance for recreation and serve as a buffer zone protecting the land from wave attack (fig. 26). Since beaches are also a source of sand for commercial exploitation, there is a strong conflict of use where the supply of sand is limited (fig. 27).

In discussing marine sediments and beach deposits we use a grain size terminology by which the particles are classified to describe the sediment texture (fig. 28). The classification is based on the diameter of the particles. In referring to sediments as sand, silt, clay, or gravel we refer to the size of the particles making up the sample(figs. 29 and 30). Sand is an accumulation of sedimentary particles having a diameter between 0.063 and 2.0 millimeters.

The percentages of size diameters of grains are determined and a mean size calculated to discuss the average size of grains in a sediment sample. The range of sizes, the sorting, is determined statistically (fig. 31). These properties, along with the mineral composition are used to describe beach sediments.

A logarithmic or geometric type scale is best suited for describing sediment size distributions. A geometric series is a progression of numbers of such a nature that there is a fixed ratio between successive elements of the series.

The distribution of size of sediment grains agrees with a normal probability distribution if powers of two are used for the diameter in millimeters. If we use the exponents --the powers of the base 2-- we have a convenient logarithmic scale of sediment size. Because most sediments are finer than one millimeter, we use the negative logarithm to the base two of the particle diameter in millimeters in what we call the phi notation:

$$\phi = -\log_2.$$

Beaches along continental shores consist predominantly of terrigenous minerals derived from the disintegration of rocks. Because quartz (fig. 32) is the most stable of the common minerals it is most abundant in mature beach sands. Most beaches also have an admixture of feldspar and ferromagnesian rich minerals. The heavy minerals magnetite and ilmenite are present in many beaches.

In the southern part of Florida, the Caribbean, and tropical regions calcium carbonate shell fragments are common constituents of beach sands (fig. 33). These sands are made of mollusk shell fragments, coral, foraminifera coralline algae, and echinoid and gorgonian spicules. Because of the abundance of volcanic rock in much of the Caribbean, the beaches may have volcanic rock fragments, serpentine, and dark minerals as common constituents (fig. 34).

The direct source of much beach sand is the shallow sea floor, where sand was carried by runoff from the land. A minor source is from wave erosion of sea cliffs. If the cliffs is alluvial material that is lightly cemented or unconsolidated, cliff erosion may be an important sediment source.

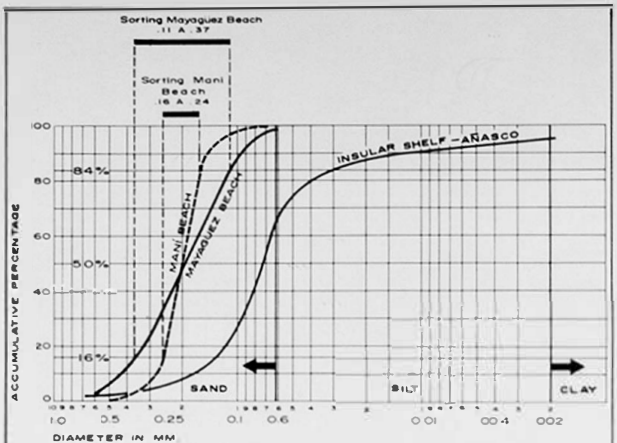



Fig. 31 grain size distribution plots.
Beach sands plot as a normal probability curve on semilog paper. The vertical axis is cumulative percent of the total and the horizontal axis is grain size in millimeters diameter. The two samples are 98 to 100 percent sand size material. The spread of sizes or range between the 16th and 84th percentiles is a measure of sample sorting. The Mani sample has much better sorting than the Mayaguez beach sample. The sorting is a function of source materials and wave energies.

The sample from offshore of Mani Beach is a sand and silt mixture with a small amount of clay.
sand 62% silt 33% clay 5%

Fig. 32 quartz sand originates from the mechanical and chemical breakdown of igneous rock such as granite. The material is transported to the sea by rivers. Angular sand grains are relatively young. Polished and rounded grains result from transportation of the material and wave action in the surf zone.

Fig. 33 carbonate sand made of the shell material of marine organisms is common along much of the Puerto Rico coastline. The material is transported from shallow offshore accumulations of shell material, often associated with coral reefs.

Fig. 34 beach sand of igneous rock fragments and dark minerals. The disintegration of volcanic and basic igneous rocks such as basalt result in dark sand beaches found along much of the south coast. Relatively large accumulations of magnetite are often found in these beaches.

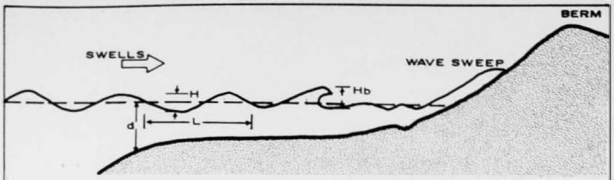



Fig. 35 wave nomenclature

Waves are generated by the wind blowing off the surface of the water. The wind sets up ripples on the water surface and these grow into waves with a sheltering effect on their lee sides. This leads to propagation of the waves in the direction in which the wind is blowing. The dimensions of waves are given as height, which is the difference in elevation between the crest and the trough, and length, the distance between two adjacent crests. The time in seconds for the passage of two wave crests past the same point is the period.

Waves may be generated locally, or may have moved out of a generating area and no longer be under the influence of the wind. In the latter case the waves are termed swell. As a wave enters shallow water the wave speed and wave length decrease and the wave height increases, until the crests steepen to sharp peaks separated by relatively flat troughs.

Fig. 36 wave refraction diagram from waves approaching the Malecon industrial area (Mayaguez) from the northwest.

The spread of wave orthogonals is divergence and the packing together of orthogonals is called convergence. Wave convergence concentrates more energy into an area and increases breaker height, and divergence reduces the energy reaching the coastline.

The effect of the shoal reef area in breaking the pattern of wave energy is evident in this figure. The northern part of the bay is protected from strong waves, and in general the energies are less than would be encountered were the reefs not present. The longshore transport of sand is to the south.

In tropic regions, the biogenic sands are derived from the remains of marine organisms, often associated with coral reefs. Beaches may also be supplied by sands that were deposited on the continental shelf during the Pleistocene stage of low sea level. Such relict sands are common on the shallow shelf. Rivers and estuaries may carry sand to the beaches, but estuaries may also trap most of the sediment.

The energy applied to the coastal zone is preponderantly from wave action. As waves approach the coast they are modified by a process of refraction which governs the final distribution of energies and generation of longshore currents. At depths of water where the ratio of water depth (d) to wave length (L) is less than 0.5, the wave motion begins to be affected by the bottom (fig. 35). Since each part of the wave travels with a velocity that is dependent on the depth, the wave must change direction of approach and conform to the bathymetry as it shoals. In addition to a decrease in velocity and change of direction of approach, there are other variations in wave characteristics as the wave shoals:

wave heights increase
wave energy is reduced
wave lenghts decrease

Wave period remains constant during the shoaling, and the period, or time in seconds between wave arrivals, may be used to estimate the deep water wave length.

Wave refraction and energies are extremely important in modeling the configuration of the coast. The analysis of the results of wave refraction are done by construction of refraction diagrams (fig. 36). The orthogonal technique of analysis lends itself to computer techniques. Orthogonals are the wave rays drawn at right angles to the crest of approaching waves

the direction of travel as the wave train approaches the shore. The distance between orthogonals is constant in deep water, representing a condition of equal power between any two wave rays. The variation in width between orthogonals as they change direction to conform to the changes in bottom topography represent equivalent changes in energy concentrations. With this method, if we assume that no energy is transmitted between orthogonals, it is possible to estimate variations in wave heights and wave energy along the coastlane resulting from wave refraction. These concentrations or divergences of wave energy lead to an interpretational process along beaches.
As the wave approaches the beach, the speed of wave travel slows, but the orbital motion of the water particles increases. A point is reached where the wave breaks because the particles in the crest are traveling too much faster than the wave train. This point is defined by the relation between the increased wave height (H) and the decreasing wave length. The wave steepness is defined as H/L, and the wave will break when the ratio is greater than 0.14 (fig. 37).

Since water from the breaking wave is carried toward the beach, there must be some way for this water to return to the sea. Part of the return is through the bottom, and part flows back under the incoming waves, but a portion of the excess water piles up between the breakers and the shore. The process of refraction is incomplete and the waves approach the beach at an angle, creating a component of movement of water along the beach called a longshore or littoral current (fig. 38). This drift of water will continue until the excess water moves offshore in a rip current, a narrow, high

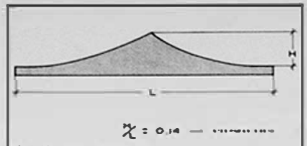



Fig. 37 wave steepness
When water depth is about equal to the wave length, the wave collapses and particles of water rush forward as a breaking wave. The actual breaking point is determined by wave steepness, the ratio between wave height and wave length.

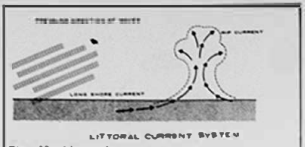



Fig. 38 littoral current system
The approach of waves diagonal to the shore sets up currents inside the breakers. Excess water is piled up between the breakers and the shore; the return flow has a longshore component which is usually confined to the surf zone. This water is returned seaward in the form of rip currents, which are high velocity seaward flowing surface currents.

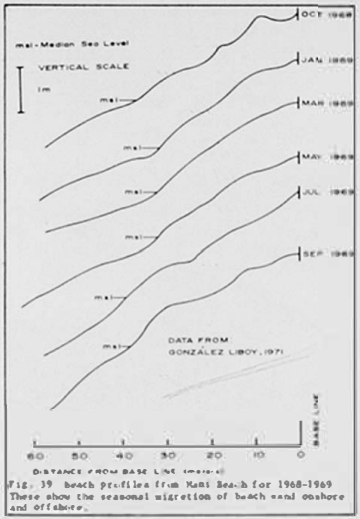



Fig. 39 beach profiles from Mahi Beach for 1968-1969
These show the seasonal migration of beach sand onshore and offshore.

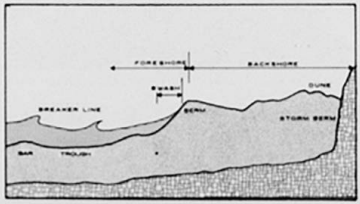



Fig. 40 beach terminology
The nomenclature of beach features is well established because of the importance in connection with legal practice arising from disputed ownership of beaches and lawsuits over the erosion of beach property.

offshore - the breaker zone directly seaward of the low tide line

foreshore - the sloping part of the beach lying between the berm and the low tide mark

backshore - the zone of beach lying between the foreshore and the coastline

shore - the zone from mean low water to the inner edge of wave transported sand

shoreline - the line where land and water meet

coast - broad zone directly landward from the shore which includes sea cliffs and elevated terraces as well as the lowlands inside the shore

coastline - the demarcation between shore and coast. The shoreline migrates constantly because of winds, tides and changes but the coastline is more stable, although beach processes are constantly altering it

berm - the nearly horizontal part of a beach inside the sloping foreshore

berm crest - the seaward limit of the berm

beach face - the sloping section of the beach below the berm that is exposed to the uprush of waves

bar - an elongate submerged sand body

swash - the uprush of water along a beach face, the upper limit is marked by the swash mark

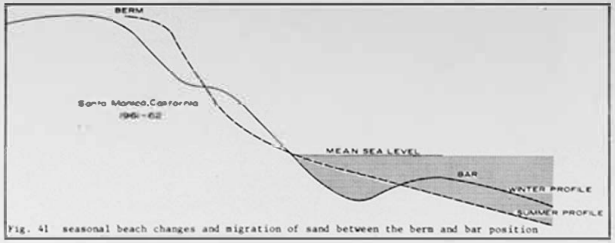


Fig. 41 seasonal beach changes and migration of sand between the berm and bar position

velocity flow of water directed away from the beach. The longshore currents are generally too slow to erode sand grains, but turbulence in the surf zone will keep grains in suspension and they will move with even a low velocity current.

Almost all beaches are subject to frequent fluctuations in size and shape. Repeated measurement of beach profiles are used to study seasonal beach cycles (fig. 39). A large part of the movement of beach sand consists of an exchange between offshore bars and the berm, the nearly horizontal deposit of sand at the top of the beach (fig. 40).

Bars are products of erosion since they appear when strong wave action cuts back the berm and moves material offshore. The formation of bars is related to wave steepness. The incoming waves are, in turn, modified by the bars. Bars act as wave filters; smaller waves pass over without breaking, but larger waves break over the bar and reform inside as smaller waves.

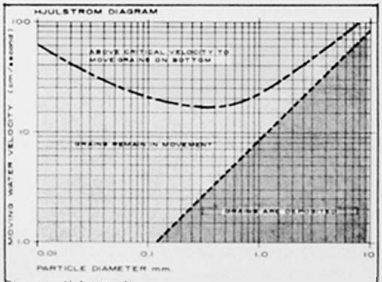


Fig. 42 Hjulstrom diagram
The critical velocities at which a grain of a particular size will be eroded from the bottom, deposited on the bottom, or transported if in suspension are given by this plot of grain diameter (in millimeters) versus current velocity (in centimeters per second). The diagram was constructed from experimental data and illustrates that once grains come to rest on the bottom, higher current velocities are required to move them than while they are in suspension

Fig. 43 accreting beach, Punta Cabullon
The long curving lines mark former beach positions, and show how the land area has grown as beach sands were added to the coast. In the modern environment, there is severe erosion of this system immediately east of Punta Cabullon.

After the stormy season, wave steepness decreases and sand is moved shoreward (fig. 41). The material from the bar migrates to the berm, building it seaward. Except on very flat beaches, the berm usually has a well defined edge, the crest, and the method of growth can be observed by watching the action at the crest. As each wave reaches the beach face, its remaining energy is spent in a thin swash of water carrying sand upward. Part of the water sinks into the beach and does not return as backwash. Thus the energy in the returning water is less, and sand is added to the berm at the crest.

The material removed from the berm by storm waves normally returns with calm weather. However, extreme wave conditions may carry the sand to depths so great that normal waves cannot reach it, and the material is lost to the system.

The onshore-offshore migration depends on a complex interaction between wave height and period, sand grain size, beach slope, tide stage, and wind conditions. Studies of orbital velocities in the surf zone show that the velocities of onshore motion are greater under advancing wave crests than the offshore motion under the troughs (fig. 42). During periods of low waves, differential velocity is sufficient so that sand will move upslope and onshore except in zones of rip currents. This onshore migration is particularly large during the advent of long period waves when there is more time for the sand grains to be deposited -- once deposited on the bottom, the grains are harder to move than sand that is in suspension. When high waves of short period keep the sand in suspension, the beach retreats because sand washed off the foreshore by backwash does not settle

until it is carried into a rip current and has moved into relatively deep water.

Since beaches receive new supplies from runoff and erosion of the land and from offshore shell material produced by marine organisms, it should follow that the beaches would grow continuously wider, unless some means exists of disposing of the excess sand. In some cases there is growth and builup of beaches, but generally sand is disposed of in several ways and is lost to the beaches, either permanently or temporarily (fig. 43).

We have already described the effect of excessively high waves moving sand so far downslope that it is lost to the beach cycle. Some of the sand that is carried downcurrent along the shore in the littoral drift is deflected seaward at the lower end of the beach system. If deep water conditions exist close to shore, the sand may be lost. Studies have shown that sand may bypass rocky points and continue along the shore, provided the water off the points is less than 10m. (fig. 44).

Fig. 44 rocky beach termination

Fig. 46 loss of sand from the beach system as wind blown dune deposits

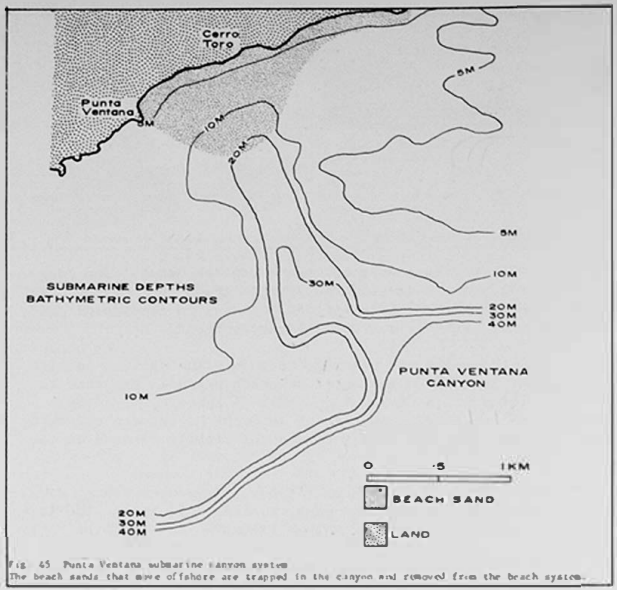



Fig. 45 Punta Ventana submarine canyon system
The beach sands that move offshore are trapped in the canyon and removed from the beach system.

Rip currents may also carry the littoral drift sand into water depths that are beyond the normal return beach cycle depth. Sand may be quickly lost where littoral drift or offshore movement encounters unusual depths such as a submarine canyon (fig. 45). The presence of canyons close to shore and of rocky points bordered by deep water, may result in a series of closed beach compartments. There is an irregularity of contours on the insular shelf of Puerto Rico, and an apparent abundance of submarine canyons and karst topography channels. There is an extensive system of submarine canyons cut into the north coast from Vacia Talega to Arecibo. These may be trapping longshore moving sand and funneling it to deeper water. There is also relatively deep water near shore at the rocky termination of many of the Puerto Rican beaches, and here again sand is probably moved offshore and lost to the beach system in these areas.

Another mode of sand loss is the formation of beach dunes (fig. 46). The wind blown sands deposited in the dunes are removed from the reach of wave action and the normal beach cycle. Land erosion may return this sand via rivers, or later erosion of the shoreline may result in direct return. If the dune sands are carried far enough inland, as into desert basins, there may be permanent loss.

PUERTO RICO COASTAL TYPES

The simplest description of the Puerto Rico coast involves a division into three basic categories:

- rocky cliff and headlands
- mangrove coast
- sand or gravel beaches

The distribution of these types of coast are shown on fig. 64.

Kaye discussed the types of shoreline along the coast of Puerto Rico. These developed in response to a number of factors including:

- the presence of a central ridge, ruptured by long strike slip faults extending from the west to the east coasts and flanked on the north and south by shallow water sediments
- the difference climatic regimes between the north and south coasts
- the transformations with time of the original features by broad climatic and erosional changes
- past tectonic activity of the area.

From Aguadilla to Punta Cabo Rojo, the coast is dominated by the effect of the termination of structural mountain ridges separated by broad alluvial valleys (fig. 47). The ridges form a rocky coast, and the shoreline bordering the alluvial valleys is occupied by sand beaches. South of Mayaguez, the shelf is relatively broad and reefs and shoals with depths of less than 10 meters extend 20 kilometers offshore. The same pattern of ridge with rocky shoreline and valley with sand beach is present, but there are also areas of mangrove coastline and fringing reef coast because of the protection offered by the shoal continental shelf area.

The southwest coast is very irregular, with projecting brush covered points of limestone between shallow coves and bays. There are fringing reefs along much of this coast. Except for the eastern and western ends of the south coast, and the Guanica area, the land is generally low near the shore (fig. 48). The shoreline development is closely related to whether the adjacent land area of the coast is Cretaceous-Tertiary limestones, igneous rock, or low Tertiary sediment fans and alluvial plains. The limestone outcrops generally form a rocky coast with small, very local sand or gravel beaches (fig. 49). In many places, this type of shoreline has been altered by the growth of mangrove and the subsequent development of a mangrove shoreline. The alluvial plains are either beach areas or unconsolidated cliffs that are retreating under the attack of strong wave action (fig. 50).

The southeast coast of Puerto Rico is mainly rocky coastline with some broad beach areas developed in front of alluvial valleys

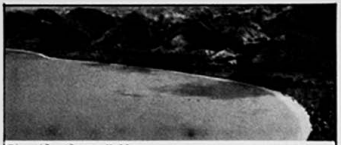


Fig. 47 Añasco Valley
This valley is bounded on the north and south by low hills that form rocky headlands.

Fig. 48 low coastal area of Southern Puerto Rico
This is a broad alluvial plain and former mangrove area.

Fig. 49 rocky coastline and pocket beaches where the shoreline is formed by limestone outcrops at Punta Verraco

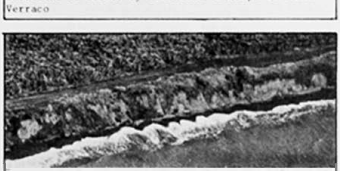


Fig. 50 cliffs of poorly consolidated alluvial plain near Playita Machete
The gravels collecting at the base of the cliffs are concentrated from the alluvium during the process of erosion and seaward transport of the finer grained material.

Fig. 51 rocky headlands and small beaches of the southeast coast at Punta Yeguas

and a few areas of fringing reef coastline (fig. 51). This pattern extends along most of the east coast where irregular projecting rocky bluffs separate numerous small shallow coves and bays. In these areas, as on the west coast, the hills are within a mile of the coast. Shoal water extends offshore as part of the platform connecting Puerto Rico and the Virgin Islands.

There is fairly widespread mangrove coast along the northern half of the east coast.

The north coast from the east end of the island to San Juan is low and sandy, except for occasional eolianite bluffs (fig. 52). The low land extends three to seven kilometers inland. The coast is indented by many coves that are protected by reefs and rocky islets lying only one to two kilometers offshore. Most of the coast is sandy beach. The large mangrove areas that lie east of San Juan do not form the coast, but lie several hundred meters behind the sand beaches and dune system (fig. 53).

From San Juan to Arecibo, the coast lies in front of a low-lying coastal plain. Beach sand, cemented dunes, beach rock, and mangrove swamps dominate this region. There are sandy beaches and dunes with ocasionally rocky eolianite coast and beachrock coast from San Juan to Vega Baja (fig. 54). The mangroves lie close to shore on the coastal plain but do not form the coastline along any part of the northern coast. From Vega Baja to Arecibo, the coast is dominantly eolianite with numerous small lunate bays bordered by beaches (fig. 55). There is some movement of the beach sand from one bay to another behind the eolianite ridges (fig. 56).

The north coast from Arecibo to Aguadilla is a series of rocky cliffs with sand beaches and dunes between them (fig. 57). The prominent features are the high hills in the interior and high cliffs along the coast. Where low coastal plains with beach are present, they are less than a kilometer in width.

The north shelf is only two to four kilometers wide and there are few offshore reefs beyond a half kilometer from shore. In most places the open ocean waves break directly against the shore. It is a high energy coast with a rugged shoreline and active beach systems.

Fig. 52 low plains and eolianite bluff at Vacia Talega

Fig. 55 north coast lunate bay, Marchiquita

Fig. 53 mangrove forest east of San Juan The dashed line shows where the mangrove ends short of the shoreline. The shore is a sandy beach behind which there are stands of palm trees.

Fig. 56 Although sand deposition is forming a tombolo connecting the eolianite to the shoreline, there is still transport of sand along the beach behind the eolianite during storm conditions.

Fig. 54 low coastal plain with a beach sand and eolianite coastline. The construction shown in this photograph is part of the regional sewer outfall system.

Fig. 57 rocky cliff of the north coast near Aguadilla

Fig. 58 Puerto Rico beach system example: Punta Ventana
This beach is bounded east and west by rock outcrops of limestone. The sands are a mixture of carbonate grains and dark igneous rock fragments and minerals. Reefs to the east supply carbonate shell material and the terrigenous component is from the old river vally of the Yauco River. (East is to the right; longshore transport is westward; Punta Ventana on left, Cerro Toro on right).

Fig 59. erosion of alluvium of the Añasco Valley at El Puente, north of the mouth of the Añasco River

Fig. 61 erosion of eolianite to form beach sands on the north coast

Fig. 60 erosion of a south alluvial cliff as a sand and gravel source, near Arroyo

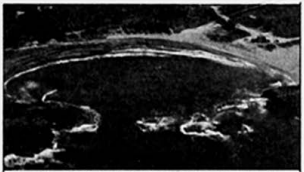


Fig. 62 Beach rock fringing a lunate bay is being eroded and added to the beach.

Fig. 63 reef sands, Enrique Reef, south of La Parguera

## PUERTO RICO BEACH SYSTEM

The coastal zone of Puerto Rico is remarkably diverse. Unlike the shorelines of many major continents, there are no long interrupted stretches of basically similar beach. The beaches of Puerto Rico are relatively short and are divided into separate and distinct beach systems that have restricted communication with one another (fig. 58). Each is a closed or semiclosed unit receiving its supply of sediment from limited local sources and transmitting little of its longshore moving sand to another beach system. In analyzing the sand and beach systems to determine the extent of isolation, mineralogy, metal content and biogenic constituents have been studied; also the actual physical parameters of separation have been analyzed.

The sources of beach sand are relatively limited and the total available volume of sand that can be added to the system is not very large. These sources include:

- offshore sands
  - modern erosional residue
  - relict Pleistocene deposits
- rivers and estuaries directly
- erosion of land
  - alluvial river valleys (fig. 59)
  - cliff erosion alluvial or rock (fig. 60)
  - eolianites and beachrock (figs. 61 and 62)
- biogenic material
  - from coral reefs (fig. 63)
  - shell accumulations

## DRAINAGE BASIN AND BEACH COMPOSITION

The beaches of Puerto Rico contain sand grains derived from three major sources. Erosion of land areas and transport of rock material by rivers to the beach supplies terrigenous sand grains. The composition variances are a function of the source area where the material is eroded and added to the river sand system. Areas of river drainage underlain by basaltic type rocks supply dark minerals and dark igneous rock fragments. Granite rock outcrops supply quartz and feldspar to the beach. Feldspar is a relatively unstable mineral that breaks down to clay minerals. The presence of feldspar in a beach system is indicative of a geologically young environment.

Calcium carbonate is supplied to the beach by the shoreward transport of the shells of marine organisms. The composition changes in calcium carbonate and terrigenous material are a function of available supply and transport system.

Along parts of the coast containing major rivers, there is an increase in terrigenous content in the beach sands. There is also a shift toward terrigenous beaches where an offshore carbonate source is lacking. By analyzing the availability of supply we can draw conclusions about the transport system and beach dynamics. Larger concentrations of calcium carbonate can indicate shoreward transport. In an area such as Guanajibo Beach (Mayaguez) the absence of carbonate grains in the beach sands coupled with the presence of reefs just offshore shows that shoreward transport of beach material is negligible. This is part of the reason for the severe erosion on this relatively protected beach environment.

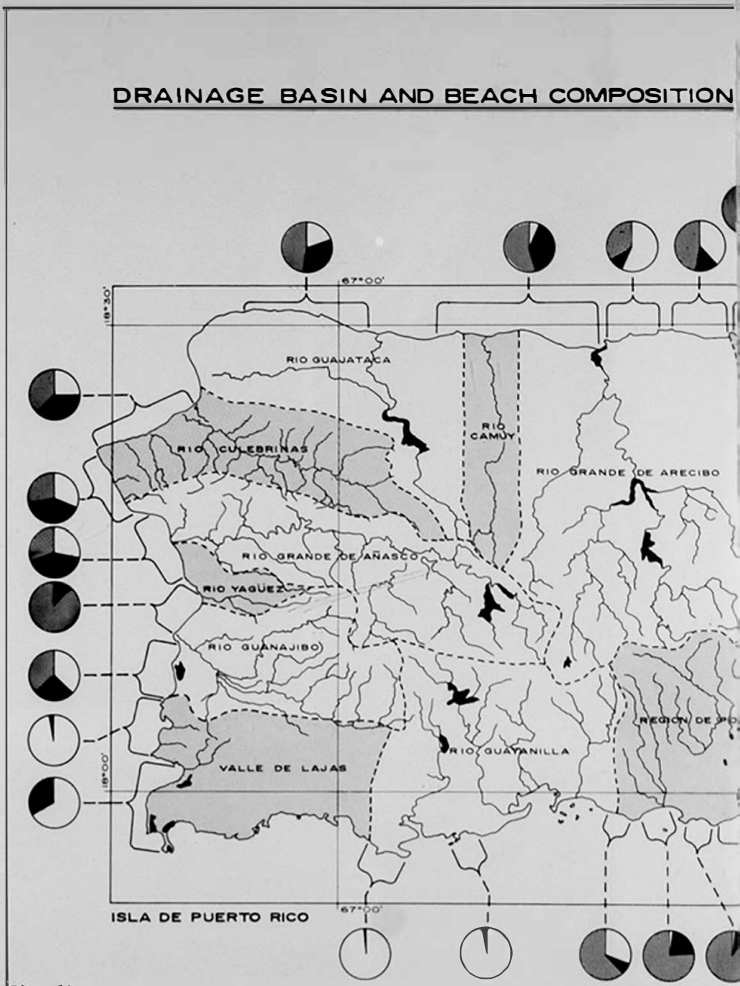
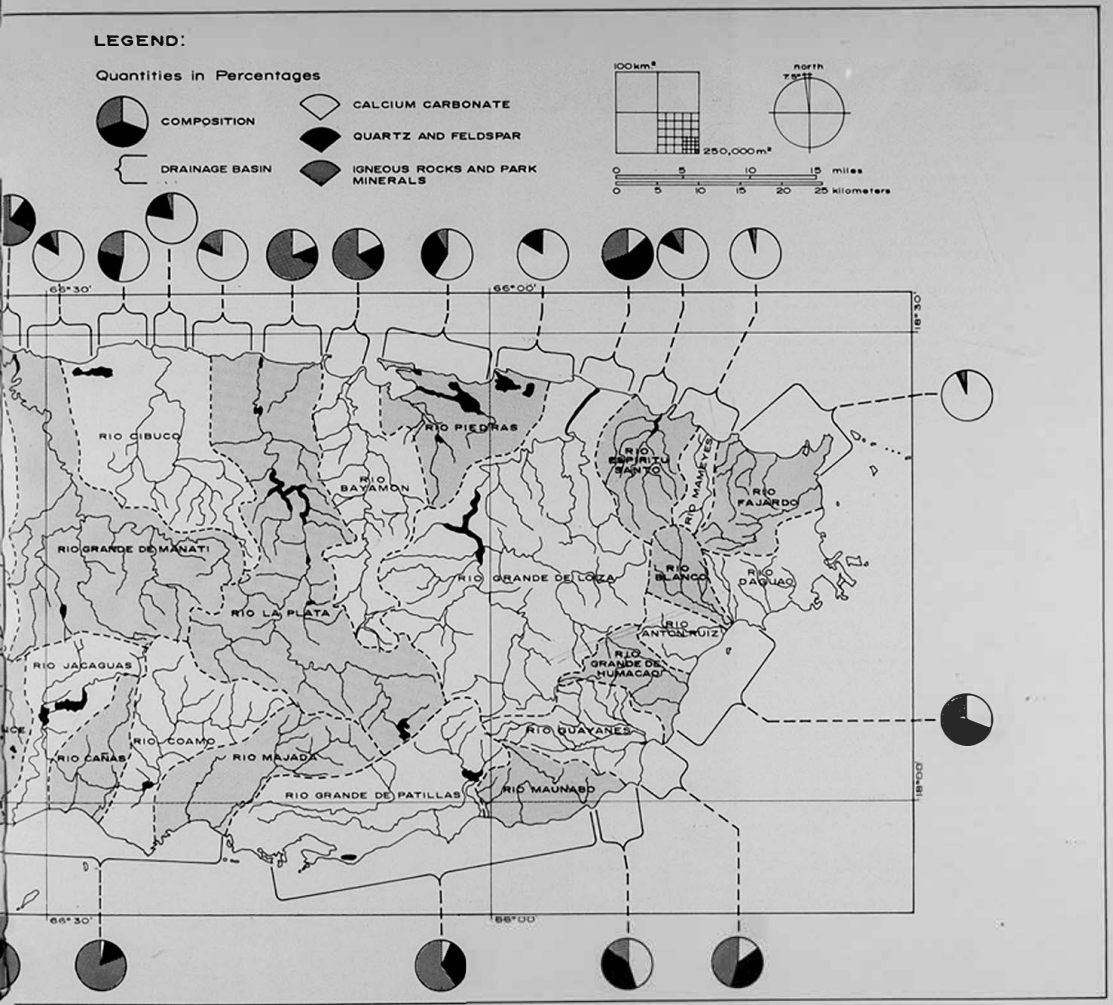


Fig. 64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COMPOSITION
DRAINAGE BASIN
CALCIUM CARBONATE
QUARTZ AND FELDSPAR
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north
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0 5 10 15 20 25 kilometers
66°30'
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18°30'
18°00'
RIO CIBUCO
RIO PIEDRAS
RIO BAYAMON
RIO ESPIRITU SANTO
RIO MAMEYES
RIO FAJARDO
RIO GRANDE DE MANATI
RIO GRANDE DE LOIZA
RIO BLANCO
RIO DAGUAO
RIO LA PLATA
RIO ANTON RUIZ
RIO GRANDE DE HUMACAO
RIO JACAGUAS
RIO GUAYANES
RIO COAMO
RIO CAÑAS
RIO MAJADA
RIO GRANDE DE PATILLAS
RIO MAUNABO

## BEACH EROSION

Fig. 65. Quebrada Cedros
Man made erosive situation. The extraction of sand from the dunes has proceeded until the depth of the water table has been reached (the dark, wet sand in the center of the photograph). There is a very narrow barrier between the excavation and the ocean with walls steeper than the angle of repose (35°) of dry unconsolidated sand.

Fig. 66. Isabela
Removal of sand from the beach for construction has resulted in movement of the shoreline landward.

Fig. 67. Cibuco
This is an area of natural erosion. The wave action is causing the cutting of a low cliff into permanent vegetation that has grown over the old beach flat.

Fig. 68. Punta Salinas
The tombolo that forms this point (a depositional feature) is now being eroded on the east side as part of the new (man made) Levittown bay circulation system. There is transport of sand from the east and west arms of the bay to the center, and then offshore transport into the bay.

Fig. 69. Levittown
This is an area of natural erosion that has been influenced by the change in bay configuration by construction of the solid causeway connecting Isla Cabras to the mainland. This has formed a deep lunate bay in which the retreat of the coastline is accelerated. Beachrock is exposed at the beach and offshore with a deep water area between. The offshore transport of sand has resulted in rapid erosion during the last ten years.

Fig. 70. Boca de Cangrejos
This is an area of natural erosion that has been influenced by man's activities. The jetty protecting the channel and the natural feature of Punta Maldonado separate this area from the sand supply to the east. The erosion of this area supplies sand to the beaches to the west in turn. Therefore, the riprap that protects the highway may cause increased erosion west of this beach.

Fig. 71. East of Maldonado Point
Removal of sand from the beach for the airport construction has exposed beachrock at the coastline and accelerated the erosion of this beach.

Fig. 72. Vacia Talega east
The erosion of the beach west of the Loiza River has been accelerated by the removal of sand from the Loiza River mouth bar. This is part of the littoral drift sand supply to the beach west of the river mouth.

Fig. 73. East of the Loiza River
Natural erosion, probably increased to some extent because of sand extraction from the bar at the mouth of the Loiza River.

Fig. 74. Punta las Carreras
Natural erosion. The sand movement is to the west and the eroded material is being added to the longshore transport system west of here.

Fig. 75. Rio Anton Ruiz
Natural erosion

Fig. 76. Jobos - Las Marias
Natural erosion. The sand movement is to the south west-west. The jetty at the port entrance is collecting small amounts of sand, but in general erosion is severe on both sides of the jetty.

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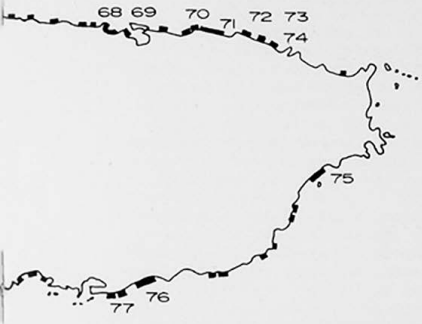

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Fig. 77 Escuela Pozuela
Natural erosion. The large waves and surf on this part of the coast has resulted in severe natural erosion. The transport of material is to the west. The cutting of a ship channel and addition of jetties may have some effect, but unlike areas where the jetties are causing increased erosion, there is no deposition east of the jetty system, this side is also eroding except immediately at the jetty.

Fig. 78 Pastillo
Natural erosion. The addition of junked cars as a form of riprap has been tried in several places along the coast. The results have not yet been investigated, but this generally results in the spread of rusting metal parts and unpleasant consequences for public use of the downstream beaches.

Fig. 79. Mayaguez - Guanajibo
Flooding of the Guanajibo valley cut into riprap, land, and highway. The highway and riprap have been restored since this flood.

Fig. 80. Erosion in the Mayaguez area has resulted in the partial loss of several houses. The normal process of erosion has been exaggerated by the activities of man. Construction close to the beach has required the addition of riprap (rock boulders) to the north end of the beach to slow the erosion. This erosion was supplying sand to the beach area to the south, so that erosion simply shifted south, requiring additional riprap. The coast is now entirely riprap boulders. The rate of erosion has been minimal during the past two years.

## BEACH EROSION

Examination of the coast by aerial reconnaissance, beach surveys, and comparative analysis of aerial photographs shows that there is severe erosion on all coasts. The data available for the Caribbean, Central America, Mexico, and the southern part of the United States indicates that erosion is the dominant activity in the beach and coastal areas. There was a history of aggradation beginning roughly 5,000 years ago and then a shift from deposition to erosion during the past 500 years. Although the rate of beach erosion fluctuates, there is presently a general state of recession of Caribbean beaches and shorelines.

The causes of this erosion may be:

- changes in sea level
- diastrophism
- erosion of barrier reefs and eolianites
- activities of man
- maturing of the system

These factors are not isolated, but are complexly inter-related. Although the rapid rise of sea level ended some 5,000 years ago, measurements lead some geologists to believe that there has been a slow rise of several centimeters during the last fifty years. In an area of limited tidal range such as Puerto Rico, a rise of several centimeters would lead to changes in the beach equilibrium. However, the change from aggradation to erosion throughout the middle America region is not synchronous as would be expected if the controlling mechanism were continued sea level rise.

Diastrophism, producing changes in the height of the land by vertical rise or fall, also affects the stability of the shoreline. If the land has dropped relative to sea level, there would be increased erosion. These movements and the accompanying effect may be local in nature.

The eolianites and beachrock along the north coast of Puerto Rico form a relatively continuous barrier which protects the shore. Behind this protection, lagoons, tombolos, and other depositional features have formed. This protection is being breached and removed by the natural force of the waves. Where the eolianite is breached, erosion has cut into the land to form lunate bays. Because eolianites on the north coast are loosely cemented, they are being reduced in height and are being destroyed, allowing waves to penetrate to the beaches with greater force. This has upset the established equilibrium and caused retreat of the shore and erosion of the beaches. Beachrock is separated from the coast by tens of meters in many places, indicating recent erosion.

Many beaches are protected by fringing and offshore coral reefs. Increased sedimentation and other factors have led to the diminished ability of many of these reefs to survive, with a resulting increase in coastal erosion as they cease to be a

barrier to wave energy. The development of agriculture on the Island and later heavy urbanization and industrialization have been major factors contributing to the loss of reefs.

Human activity is important locally. The activities of man have been varied and striking in contributing to the loss of coastal areas. In some cases the natural transfer of sand from one area to another has been blocked by the construction of new structures such as the causeway between Punta Tocones and Isla de Cabras. This has not only cut off a source of sand nourishment, but has altered the prior circulation patterns, and tombolo of Punta Salinas is now being eroded.

Removal of sand from river mouths includes the collection of littoral drift sand and results in severe erosion such as that seen near the mouths of the Añasco and Loiza rivers. Removal of sand dunes and beach sand for use as fill and aggregate have certainly contributed to the depletion of many beach systems. In areas where sand dunes have been removed, leaving only a small barrier, waves have started to break over the barrier and are carrying sand away.

Construction activities have crowded close to the shoreline because of limited land areas and reduced construction costs. This has not only aggravated the erosional process, but has put valuable new property in areas of natural erosion. This has in turn created the need to institute urgent and expensive protective techniques to protect the investment. These remedies may have effects not immediately recognized. Construction close to the beach south of Mayaguez Harbor was being rapidly endangered by erosion. Riprap was emplaced to protect this property, which then cut off a source of sand -- natural coastal erosion -- from the area to the south. The next step was riprap protection for houses to the south which were being threatened by the erosion generated by the riprap. As the problem moved south, the entire beach was eventually replaced with riprap. The coast is now stabilized, with a basic change in coastal classification from sandy beach to rocky shoreline, man-made.

It has been suggested that the broad change from aggradation of beach and coastal land to the present widespread state of erosion is part of maturing of the system. The entire process may be an evolving adjustment to the present sea level. There are many areas in Puerto Rico such as the accretionary beach ridges east of Ponce, the Humacao coastal region, and the many tombolos that show past periods aggradation. There is also evidence of a shift to erosion in these same areas.

Beaches are fragile and transitory geological features and require care and consideration if we are to transmit to our children's children the joys of a day at the beach.

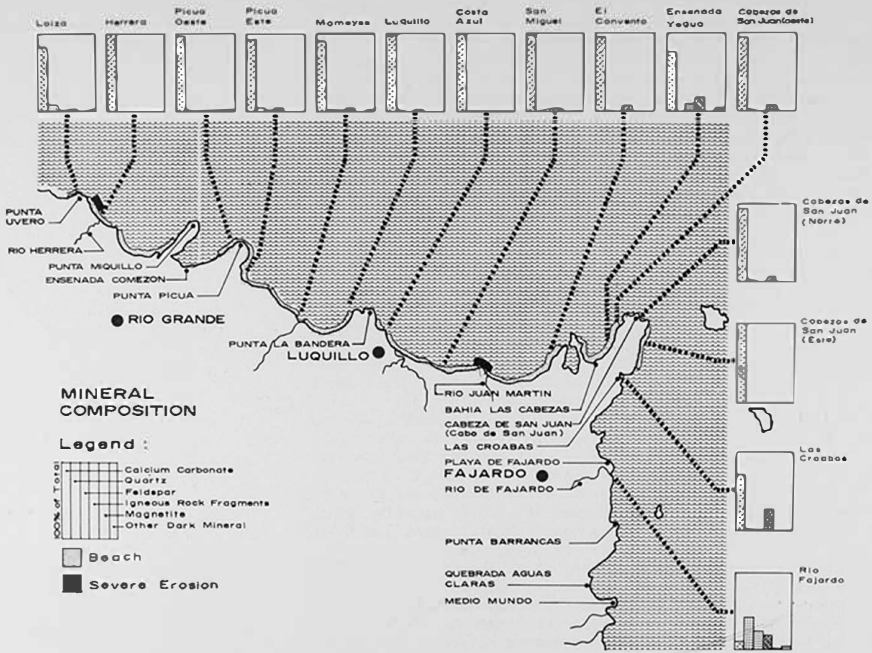



Plate 1

Fig. 81. South of Fajardo, garbage dump in mangrove. Narrow sandy beach is fronting the mangrove.

Fig. 82 Punta Picua, Hyatt housing development. Wide sandy (carbonate) beach with numerous offshore shoals, no erosion of beach zone, major removal of mangrove just west of this area.

Fig. 83. Punta las Carreras, narrow sand beach, carbonate, quartz, and igneous rock fragments. Severe erosion in this area is cutting into the shore as evidenced by rapid undercutting of palm trees.

COASTLINE AND BEACH ANALYSIS

The southern part of Medio Mundo is a mangrove coast and the northern part is beach plain. North of Quebrada Aguas Claras, there is a short mangrove coast and then northward a rocky shoreline to Punta Barrancas. From here to Playa de Fajardo the coast is mangrove (fig. 81). From Fajardo to Cabeza de San Juan, the shoreline is fringing reef with a narrow beach developed behind the reef. Bahia Las Cabezas is a beach plain and west of this there is a narrow stretch of fringing reef coast. The coast westward to San Juan is beach plain with the exception of a limited amount of mangrove coastline at Ensenada Comenzon, a barrier coast at the mouth of the Loiza River, and an eolianite coastline at Punta Vacia Talega and Punta Maldonado. Much of this coast is partially protected by a narrow band of shoal offshore reefs and rocks. Reef development is especially strong off Punta La Bandera, Punta Picua, Punta Miquillo, and from Punta Uvero to Punta Iglesia.

There is a narrow, fine-grained beach at Playa de Fajardo composed of quartz, feldspar, and igneous rock fragments. Most of this sediment has been carried by the Fajardo River. The beach is interrupted in several places by riprap, but erosion does not appear to be severe. Bahia Las Cabezas and Las Croabas beaches are narrow carbonate beaches lying behind a fringing reef which supplies most of the beach material. There are igneous rock fragments in the Las Croabas beach, derived from local sources. Neither of these beaches shows signs of severe erosion.

From Cabo San Juan to Rio Herrera, the beach sands are carbonate shell material derived from offshore. Minor amounts of quartz, feldspar, and igneous rock material are supplied by local erosion. The beaches are relatively broad and essentially continuous. Rocky outcrops interrupt the beach system at the point west of Rio Juan Martin and Punta La Bandera. At Punta Picua, there is also an interruption of the beach, but from composition and bathymetry it appears that a single beach system is present from Cabezas de San Juan to Punta Vacia Talega (fig. 82). The increases in quartz and heavy minerals near the Herrera and the Loiza Rivers are local additions of sediment by the rivers. The sand bypass from one beach to another in the shoal offshore zone.

Fig. 84. Rio Loiza, double bar development across this river mouth shows both east and west sand drift. Shoal mouth is blocked and causes flooding of lowlands if the channel is not maintained.

Fig. 85. Tres Palmitas. There has been severe erosion following removal of sand for construction at Isla Verde. There is now a narrow beach behind exposed beachrock and riprap.

Fig. 86. La Concha jetty. The construction of this jetty has formed a wide bathing beach by trapping the westward migrating sand.

Between Punta Uvero and the Loiza River, there are several areas of severe erosion. Just east of Punta Uvero to Rio Herrera and east and west of Punta Iglesia and Punta las Carreras there is erosion (fig. 83). In both cases, this is strikingly shown by palm trees in the ocean, many of them lying at the water's edge.

The composition of the Loiza beach from Punta Uvero to Vacia Talega is strikingly different from the rest of the beach system in having a very high quartz content. This is contributed by the Loiza drainage system (fig. 84). Erosion is markedly severe from the mouth of the Loiza River halfway to Punta Vacia Talega.

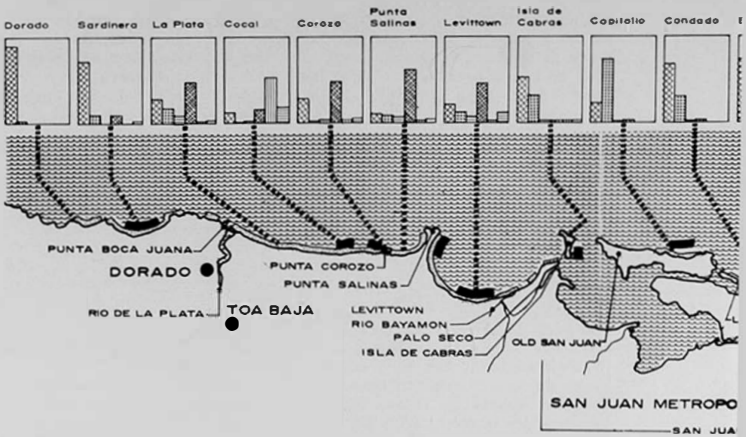
West of Punta Vacia Talega there is an entirely different beach system from the Luquillo beach complex and specifically from the Loiza beach. Quartz is almost absent from the beach sands which are 70 to 95 percent calcium carbonate of marine shell origin. The Loiza sands are apparently carried offshore in passing Punta Vacia Talega and only limited amounts return to the beach. Erosion is severe west of Punta Vacia Talega (fig. 85). There is a high stabilized dune system behind the beach which is affording some protection to the land area. The beach foreshore is relatively steep. Maldonado Beach is a short, narrow beach between Punta Maldonado and Punta Cangrejos. Erosion is severe on this beach

From Boca de Cangrejos to Punta Chivato the coast is beach plain interrupted by numerous outcrops of eolianite, forming an eolianite shoreline, and several local beachrock coastlines (Cibuco and Puerto Nuevo). The mouth of Rio de la Plata is a barrier coastline.

The beach sands from Boca de Cangrejos to Old San Juan are a mixture of carbonate grains and quartz. There are about seven separate beaches separated by rock outcrops, but the water depths and composition indicate that there is probably transference of material from one beach to another resulting in essentially one beach system. The addition of a jetty at La Concha (fig. 86) has interrupted the westward migration. There are sand deposits in deep water (40-50 meters) off Boca Cangrejos which may result from the offshore transport of the beach sands.

The beaches are thin coverings of sand over a rocky shoreline. Severe erosion at Boca de Cangrejos has threatened the road. The remedial action has been emplacement of riprap (fig. 87). There is active erosion at Ocean Park and Isla Verde. There is loss of sand offshore and also windblown into the streets in the Condado area. Although the composition of sand on Isla Cabras is similar to the San Juan beach system, there is probably no transport of sand across the deep entrance channel of San Juan Harbor.

From Levittown to Rio de la Plata, the beach is dominantly igneous rock fragments with other dark minerals, quartz, feldspar, and carbonate grains. There is severe erosion at Levittown and Palo Seco. The erosion of sand from behind the beachrock at Levittown (fig. 88) is fairly recent and shows the rapid changes in beach position since the construction of the Isla Cabras causeway and the Bayamon canal (fig. 89). This construction has drastically altered the current and wave patters and set up new conditions in the large lunate bays between Isla Cabras and Punta Salinas. Punta Salinas is a tombo-



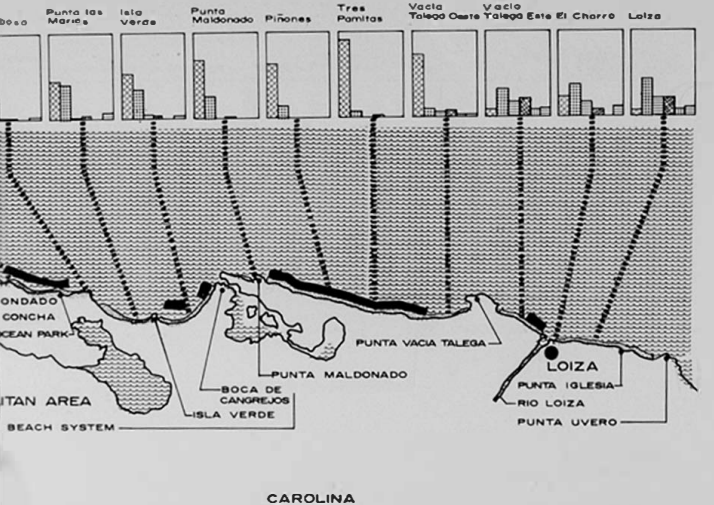

## MINERAL COMPOSITION

**Legend :**

Fig. 87. Boca de Cangrejos. Rapid erosion of the shoreline threatened the highway at Boca de Cangrejos. This has been slowed by the addition of riprap to the beach face.

Fig. 88. Levittown beach, viewed westward from near the Bayamon channel. The beach rock line --now offshore-- marks the beach position before construction of the Isla Cabras causeway and the Bayamon channel.

Fig. 89. Isla Cabras Causeway. This is a solid causeway which has blocked the passage of water and sediments from the Bayamon River and San Juan bay into the Levittown bay.



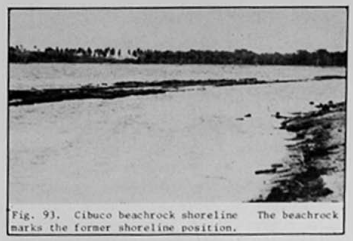



Fig. 93. Cibuco beachrock shoreline The beachrock marks the former shoreline position.

Fig. 94. Cibuco Bay The large separation of the former beach line from the present shoreline can be seen in this photograph. Also the wave patterns at the point show the zone in which sand is being deposited to form a tombolo.

Fig. 95. Boquilla Beach. Sand deposited in the zone behind the eolianite has formed a tombolo. The sand is above normal wave action, but during high waves and storm conditions may be transported along the beach.

Plate 2

Fig. 90. Punta Salinas tombolo. A tombolo is defined as an offshore rock or land mass that has been joined to the shoreline by the deposition of sand in the quiet zone behind it.

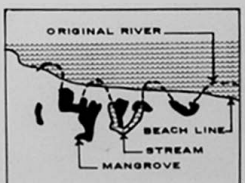



Fig. 91. Cutoff meanders of the Cocal channels. There has been erosion of this area during the last several centuries. Retreat of the beach line has cut across stream meanders that were once inland.

Fig. 92. Dorado Beach Hotel beach. The solid breakwater has eliminated beach erosion in front of the hotel. The small lunate bays are isolated from the rest of the beach system by rocky headlands both east and west.

lo of fairly recent origin that is now being eroded (fig. 90).

Within the last few hundred years there has been a marked retreat of the coastline between Punta Salinas and Rio de la Plata. There are several meanders of the Cocal channels that have been cut off by the retreating beach line (fig. 91). There is severe erosion just west of Punta Corozo that has been partially

controlled by riprap to protect the highway.

From Boca Juana to Rio Cibuco, the sands are dominantly carbonate with some quartz, except for the Cerromar Beach. This is a man-made beach, nourished by truck with quartz sand. The high level of quartz in the next beach west shows that sand transport and bypassing occurs. There is severe erosion at Sardinera beach evidenced by the continuing loss of palm trees at the shoreline. There is an input of dark minerals and igneous rock fragments by the Cibuco River. There is also severe erosion in the bay west of the river mouth.

The shoreline in this area is beachrock and is separated from an earlier shoreline by a widening expanse of water (fig. 93). The interferance of refracting and defracting waves behind the isolated eolianite shown in fig. 94 creates a zone in which sand is deposited to form a tombolo.

From Laguna Tortuguero to Peñon Afuera, the coastline is beach plair and eolianite. More of the coast is eolianite than to the east. The sands from Punta Chivato to Rio Manati are carbonate with some quartz grains and igneous rock fragments. The material is from offshore production by marine organisms and weathering of the eolianite. There are numerous lunate bays, formed by erosion of the land when the eolianite is breached, and numerous examples of tombolos, where the sand connects remnants of eolianite to the receding shoreline. In many these. there is no obstruction to the passage of sand behind the eolianite (fig. 95). Most of the beaches are thin sand deposits over a rocky lower foreshore. During winter storm periods these sands may move offshore temporarily. The Manati River carries large amounts of igneous rock material,

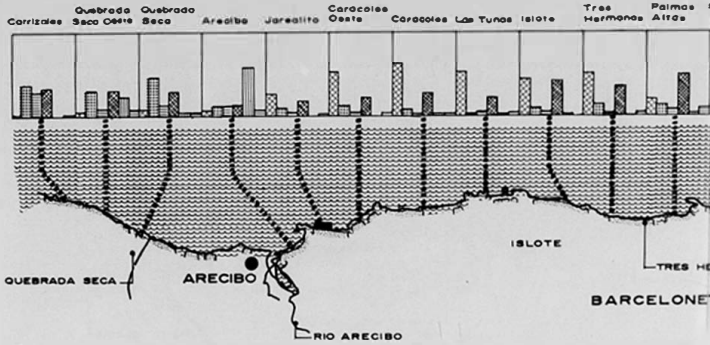
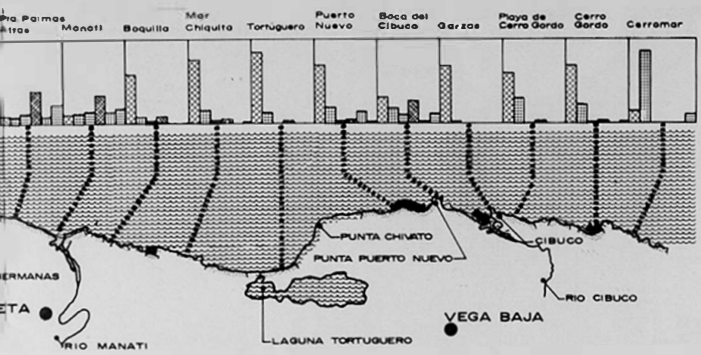


Fig. 96. Palmas Altas. The pattern of lunate bays and tombolos continues here, but the longshore transport of sand is blocked by the permanent vegetation growing on the foreground tombolo.

Fig. 97. Arecibo River distributary pattern. The river forms a broad part of the coastal plain, and inland is incised into the uplifted limestones of the north coast.

Fig. 98. Camuy River. The discharge is generally low and the river is partially blocked. There are fairly high mobile dunes behind the beach just west of the river.




dark minerals and magnetite. The beaches to the west of the river mouth are dominated by these minerals. There is a slow decrease in these grains and an increase in carbonate material toward Jarealito. Although the beach materials have been transported behind the eolianite, many of the tombolos are now stabilized by the growth of vegetation, and sand is no longer passing across the tombolo (fig. 96).

Between Tres Hermanas and Jarealito, the beach is dominantly carbonate with some igneous rock fragments. From Rio Arecibo west, the beach is quartz, feldspar and igneous rock fragments in roughly equal portions. On some of the beaches (Arecibo, Quebrada Seca West) the magnetite content is very high. Both the Arecibo and Camuy Rivers carry sediments to the beach system (figs. 97 & 98).

Near Islote, part of the beach sands are being lost from the system by wind erosion (fig. 99). The sands are being incorporated into dunes behind the beach, and evidence of recent activity is shown where the sand has blown over the vegetation.

The coastline west of Peñon Afuera is secondary type resulting from wave erosion of a rocky coast. From here to Aguadilla, the coastline is formed by the bluffs of Tertiary limestone and is shaped by wave erosion. However, in about half of the coastal areas the limestone bluff is several hundred meters to several kilometers from the shoreline, and the coastal type is beach plain. West of Jobos beach, there is a short stretch of coast that is primary, resulting from subaerial deposition by wind and is classed as a dune coastline. Eolianite coastline is much rarer than to the east.

Plate 3

Fig. 99. Formation of sand dunes in the Islote area. This sand is lost to the beach system unless returned by subsequent erosion of the shoreline.

Fig. 100. Bellaca Beach. This is a very restricted sand beach at the mouth of a quebrada. The rocky shoreline is Tertiary limestone, but the beach sands are igneous rock fragments, quartz, and feldspar.

Fig. 101. Guajataca Beach. These sands are supplied from the drainage basin of the Guajataca River. The beach is isolated from other beaches by rocky headlands both east and west.

The beach at Bellaca is a small local sand accumulation or pocket beach (fig. 100). Most of the beach material is carried to the area by the quebrada. The Guajataca beach is quartz, feldspar, and igneous rock material carried to the area by the Rio Guajataca. It is isolated from the other beaches by rocky headlands (fig. 101). The beaches east of Isabela are generally narrow, thin veneers of sand over a rocky shoreline (fig. 102).

From Del Toro beach westward, there is a thick and wide dune system behind the beaches which probably supplies most of the beach sands by landward erosion. There is no permanent drainage system into this part of the coastline, but the sands are dominantly igneous rock material, quartz, and feldspar. Carbonate grains make up only a small part of the beach sand. There are numerous rocky headlands interrupting the beaches, but there is probably lateral migration of the sands in the nearshore region.

The dunes behind the beaches have been extensively mined for sand, and in places (Sardina) the beach sands have been removed. The beach at Punta Jacinto (fig. 103) shows the wide and thick accumulation of sand that lies in front of the vegetation covered sand dunes. West of Jobos beach, there has been major removal of the dune sands (fig. 104). Both the composition of the beach, and the presence at the lower part of the beach of beachrock outcrops (fig. 105) suggests that the major source of beach sand is the dune system.

Punta Borinquen and Crashboat beaches are isolated beaches bounded by rocky shoreline (fig. 106). The beach is continuous from Aguadilla to Punta Gorda, and the coastal type is beach plain (fig. 107).

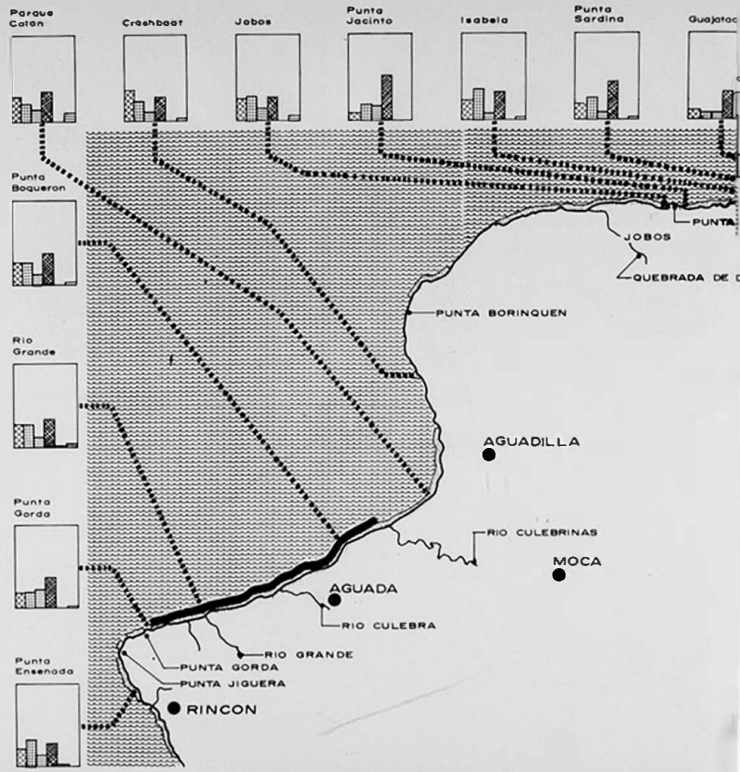
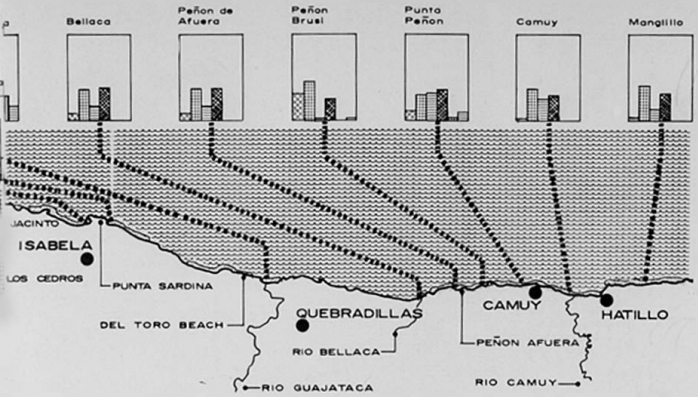


Fig. 102. Along much of this coast, the sands are a very thin veneer over a rocky shoreline. They are moved mainly by storm waves.

Fig. 103. Jacinto Beach. Igneous rock fragments make up more than 50 percent of the sand grains; the other components are quartz and feldspar. The beach has a very steep foreshore and a broad berm.

Fig. 104. Cedros-Jobos Beach. The removal of sand from the dunes has left only a narrow ridge of this once extensive sand dune system.




## MINERAL COMPOSITION

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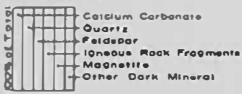



Beach

Severe Erosion

There is severe erosion from Rio Culebrinas to Punta Gorda. The beach sediments are approximately equal parts carbonate shell material, quartz and feldspar, and igneous rock fragments. Sediments from a large drainage basin are carried to this part of the coast by Rio Culebrinas and Rio Grande. Most of the coastline between Punta Jiguera and Punta Guanajibo is beach plain. There are three beach systems: Corcega, Añasco, and Mayaguez beaches. These are separated by rocky headlands at La Tosca and by man-made facilities at Mani. From Punta Guanajibo to Punta Melones there are a variety of coastal types. About half of the coast is beach plain. There are several rocky shorelines of secondary wave erosional type and several stretches of mangrove shoreline. At Punta Guaniquilla, the shore is fringing reef.

The Corcega beach sands are carbonate, quartz, and igneous rock fragments with minor amounts of

Plate 4

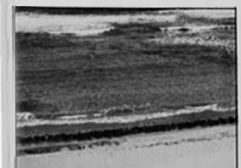


Fig. 105. Cedros Beach. The beach sands form a narrow and thin zone of mobile sediment and the lower beach face ends in ledges of beach rock.

Fig. 106. Crashboat Beach. This is an isolated beach with rocky shoreline. The sands are a mixture of igneous rock fragments, quartz, and feldspar supplied by the Quebradas and carbonate grains from offshore.

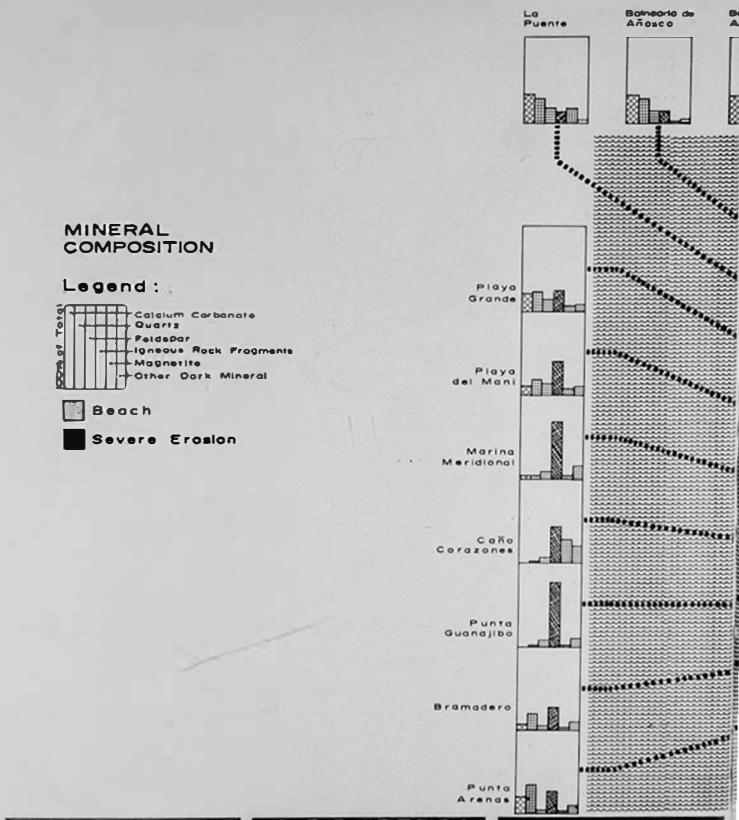
Fig. 107. Aguada. The beach plain shoreline from Aguadilla to Punta Gorda is protected in many places by riprap to slow the erosion conditions that exist along this beach.

Fig. 108. Añasco River. The longshore drift and river sediments form a bar at the mouth of the river. The channel is dredged for sand which contributes to the severe erosion at El Puente.

Fig. 109. South Mani beach. The Añasco beach system terminates at the Malecon industrial site landfill. In the 12 years since construction there has been considerable addition of sand to the deep water adjacent to the retaining wall. This is a potential source of sand for construction.

feldspar. It is a fairly broad beach with a steep foreshore face. There is strong littoral drift to the southeast, but no evidence of severe erosion except northwest of Rincon. The beach terminates at Punta Cadena, where the shoreline is rocky. Sampling off this point indicates that much of the sand is moving offshore at Punta Cadena. Some of this sand bypasses the point and is added to the Añasco beach system.

The north end of the Añasco beach is calcium carbonate with quartz, feldspar, and igneous rock fragments. There is an offshore source of calcium carbonate shell material south of Punta Cadena. The carbonate content decreases southward until at Mani beach the dominant component is igneous rock fragments with quartz and feldspar and some carbonate grains. The beach terminates at the land fill of the Malecon industrial site (fig. 108). There is severe erosion from El Puente to Mani beach north (fig. 109). The flooding associated with hurricane Eloise moved large amounts of river sand offshore. Shoreward transport of this sand has (temporarily) halted erosion at El Puente. During normal flow conditions, most of the Añasco River sand size sediments are trapped in the estuary. However, during floods and high rainfall these sands are carried offshore and some of this material may join the beach system. There is relatively little offshore movement of the sand and most of it is accumulating at the Malecon landfill site and offshore from Mani beach south. The accumulation at the Malecon landfill (fig. 110) is a potential sand source. Mayaguez beach is composed of igneous rock fragments, magnetite, and other dark mineral grains, and minor amounts of feldspar grains. The mineralogy is very



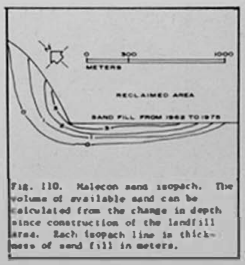




Fig. 110. Malecon sand isopach. The volume of available sand can be calculated from the change in depth since construction of the landfill area. Each isopach line is thickness of sand fill in meters.

Fig. 111. The beachfront at Guanajibo homes is dominantly riprap, emplaced to slow the erosion of beach property.

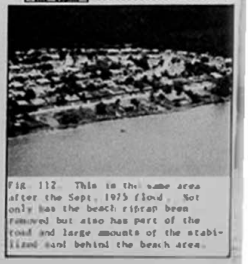


Fig. 112. This is the same area after the Sept. 1975 flood. Not only has the beach riprap been removed but also has part of the road and large amounts of the stabilized sand behind the beach area.

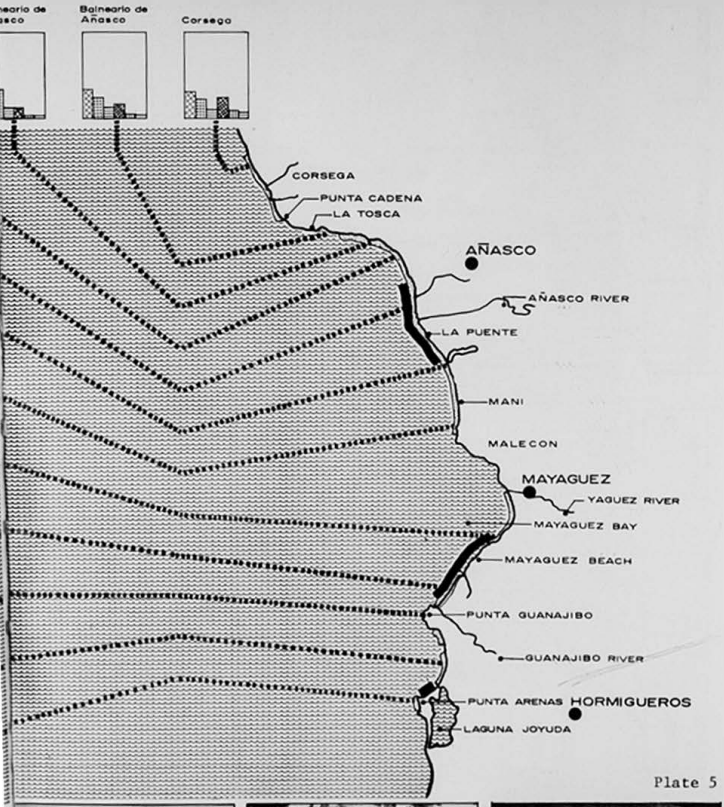



Plate 5

Fig. 113. This is the area just south of Guanajibo homes. The highway and riprap were both swept out by flood waters. Some of the ocean re-entrants into the land are as much as 1.5 meters deep.

Fig. 114. The erosion of the beach has progressed so far that total loss is a threat. The emplacement of riprap has helped stabalize the erosion, but has affected neighboring beach areas.

Fig. 115. Ostiones Beach. The sands are carbonate, dominantly algal plates from the shoal turtle grass areas just offshore.

different from the Añasco beach system. The deep water of the Mayaguez Harbor entrance blocks transport of sand from the Añasco system to Mayaguez beach.

There is severe erosion along the southern half of Mayaguez beach. Riprap has been added to long stretches for protection until the coastline is no longer beach (fig. 111). This has slowed the loss, but has also shifted the erosion to another part of the beach until riprap now extends to the Guanajibo River. The September 1975 flood made major alterations to the beach (fig. 112) and ripped out both highway and riprap (fig. 113). Prior to the flooding, the severity of the beach erosion was shown by the undermining of homes on the beach (fig. 114). The flood carried large amounts of sand offshore. Some of these sands may return to the beach system, but most will be covered by the marine silts that are the dominant sediment beyond the three meter depth contour.

The beaches south of Punta Guanajibo are carbonate, quartz, and igneous rock fragments. Some of the terrigenous materials in the beaches north of Punta Arenas are passing the rocky Guanajibo Point and returning to the beach system. At Ostiones, the beach sands are 100 percent carbonate, dominantly Halimeda plates (calcareous algae) (fig. 115). The sands at Boqueron beach are carbonate and quartz. The alluvial plains west of Boqueron are the source of the quartz grains. There is severe erosion at Punta Arenas, Punta la Mela, and southwest of Boqueron Beach.

Between Punta Melones and the Parguera forest, the coast is beach plain with short stretches of rocky wave erosion coast at Cabo Rojo and Punta Molino. There are short

expanses of mangrove coast on the west and east side of the Cabo Rojo tombolo and west of Playa Sucia. From a point just east of Punta Molino to Punta Montalva, the coastline is dominantly mangrove (fig. 116). There are areas of striking growth of land contributed by the spread of mangrove, and several former beach lines can be seen as much as half a kilometer inland.

At Parguera there is a tidal flat coastline behind fringing mangrove. The land immediately behind the coast is a low range of limestone hills that are the southern limb of a syncline. Isla Magueyes and Isla Matei are outcrops of this limestone. Visual observations, seismic surveys, and collected data show that the shelf south of La Parguera is underlain by the same limestone, and it has been suggested that the lines of offshore reefs may be localized by outcrops of the southern flank of the limestone syncline.

Both Magueyes and Matei are surrounded by fringing mangrove. Bahia Fosforescente is also bounded by mangrove. From Parguera east, there are low tidal flats and salinas behind the mangrove shoreline.

East of Montalva the coastline is formed by wave erosion of the southern limestone platform. The coast can be generally classed as secondary wave erosion made irregular by waves. There are numerous small pocket beaches of sand and gravel at the base of the limestone cliffs, with no apparent connection to one another.

El Combate beach is quartz and calcium carbonate sand. There is no evidence of strong erosion. Punta Aguila separatea Combate beach from Aguila beach which is dominantly calcium carbonate with

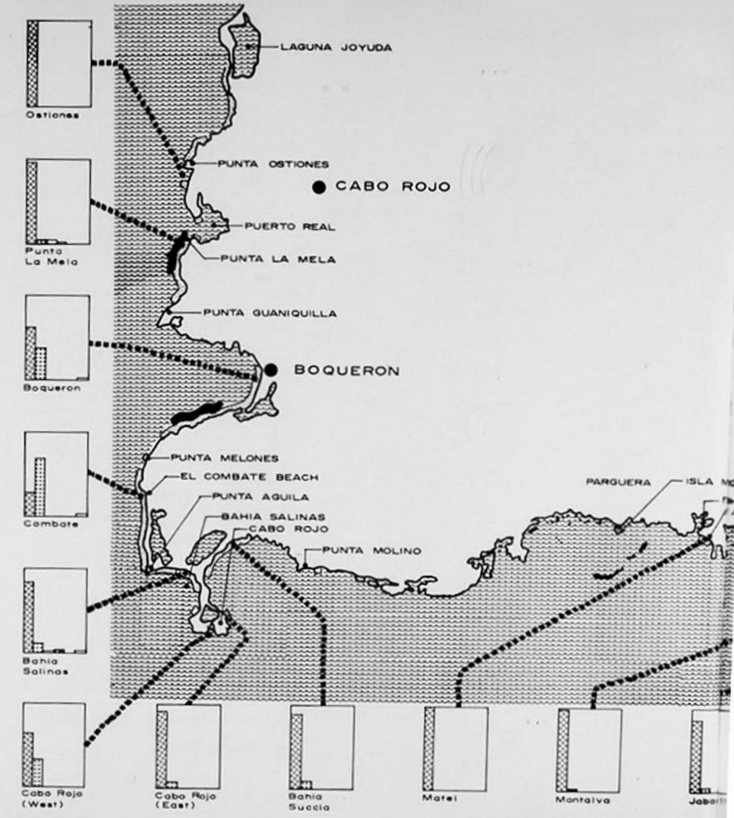


fig. 116. La Parguera mangrove forest. The growth of mangrove has extended the land area.

Fig. 117. El Combate Beach. This beach is part of the low lying west coast. The sands are quartz and calcium carbonate. There is little evidence of erosion; the longshore transport is southward.

Fig. 118. Cabo Rojo. The lighthouse is on a limestone outcrop. This is joined to the mainland by low sand deposits and mangrove swam to form a tombolo.

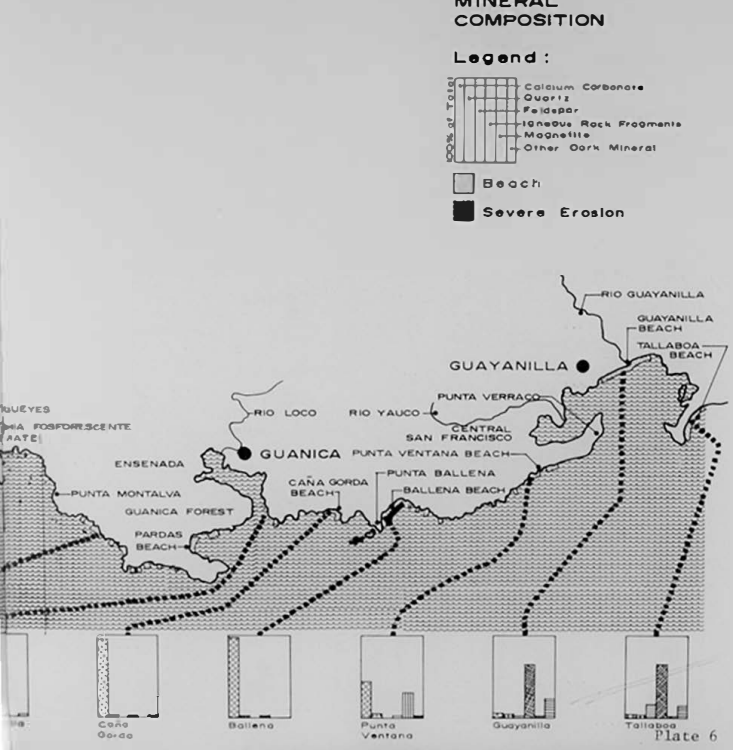



Plate 6

Fig. 119. Cabo Rojo sands. These offshore sand waves are migrating to the southwest, past the point. Since the littoral drift west of the point is southward, these sands are leaving the beach system and can be a source for commercial extraction.

Fig. 120. Montalva Beach. The construction of a condominium and urbanization has diminished the area of beach, but this remains one of the pleasant beach areas on the south coast.

Fig. 121. Caña Gorda. This public beach is one of the cleanest and most pleasant of the south coast beaches. There is easy access by highway 333, and the beach and facilities are well maintained.

minor amounts of quartz and igneous rock fragments (fig. 117). Considering the change in composition and the prevailing pattern of longshore drift, transportation of sa andbetween the two beaches is probably of limited extent. Cabo Rojo beach is a small pocket beach at the base of the limestone cliffs. It is composed of carbonate and quartz grains. Cabo Ro jo is an outlier of the limestone forming the coast and is connected to the mainland by the deposition of a sand spit which joins the two (fig. 118). This has been used as an example of a tombolo. Playa Sucia is a carbonate and quartz beach that gets its name from the unique circulation patterns in the bay between Cabo Rojo and Punta Molino. As the surface currents move westward along the south coast of Puerto Rico, part of the flow passes Cabo Rojo and continues into the Mona Passage. Part of the flow is diverted into the bay and carries surface debris to Playa Sucia. The bay contains large quantities of sand which are being moved southwest past Cabo Rojo (fig. 119). Since the longshore drift is south from Punta Aguila, this sand is being moved out of the beach system and is a potential sand source for offshore mining.

From Punta Molino east to Punta Verraco, there are only small pocket beaches at the base of limestone cliffs or isolated in a mangrove coastline. There is no evidence of communication and passage of sand from one to another of these beaches. All of the beaches are composed of calcium carbonate grains derived from erosion of the limestone cliffs and from the shells of marine organisms living offshore. The largest of these beaches are Montalva, Pardas, Caña Gorda, and Ballena.

Montalva is a pleasant bathing

beach easily reached by car from Ensenada (fig. 120). The area is rapidly being built up by construction of a condominium and an urbanization of small houses. Pardas is bounded by national forest and access for the public is difficult. Several aerial observations suggest that surface oil may be carried to this beach from Guayanilla. Caña Gorda is a public balneario with a hotel at the east end, and is a popular and pleasant beach area (fig. 121). Ballena is relatively easy to reach by the dirt road that continues along the coast past Caña Gorda. This is the only beach of this group that shows signs of severe erosion.

The small pocket beaches at the base of cliffs west of Ballena are composed of calcium carbonate sands. The beach at Punta Ventana is different in composition (fig. 122). It is a mixture of calcium carbonate quartz, and dark minerals and igneous rock fragments. The Yauco River once flowed to the coast at Punta Ventana and cut a deep submarine canyon in the shelf to the south. The quartz and dark minerals were transported to the area from the interior by the river and are relict sediments. Since the course of the river has been diverted, probably by faulting, the only modern sediments being contributed are calcium carbonate. Playa Ventana is virtually inaccessible to the public. The road to the beach runs through lands owned by Central San Francisco and signs on two locked gates warn of prosecution of trespassers.

From Punta Verraco eastward, the coastline and beaches are drastically different. The coast is a low lying alluvial plain except for a short stretch between Tallaboa and Punta Cuchara. Here the coastline is wave erosional and fringing reef. The rest of the coastline is

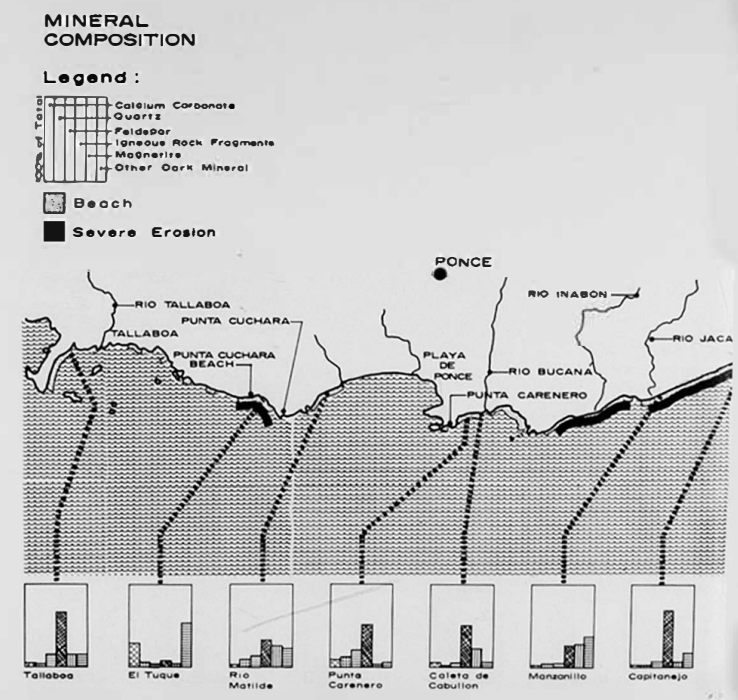


Fig. 122. Punta Ventana Beach. This limited area beach occupies what was once the valley of the Yauco River. There are considerable heavy minerals dark igneous material and quartz grains in the sands.

Fig. 123. Guayanilla refining complex. These facilities are located on a low outwash plain and mangrove coast south of the limestone hills.

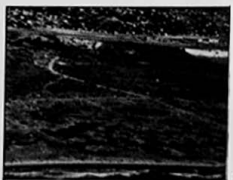


Fig. 124. Playa de Ponce. The beach is composed of igneous rock, magnetite, and dark minerals. The use of the area as a source of sand and a garbage dump has created the most unsightly beach in Puerto Rico.

either beach plain or mangrove.

The composition of the sands and distribution of beaches is very different from the preceding area. Guayanilla beach is dominantly igneous rock fragments with quartz and dark minerals (fig. 123). Tallaboa beach is dominantly igneous rock fragments with some carbonate grains and Punta Cuchara is of dark monomineralic composition with igneous rock fragments. The rocky shoreline between these two beaches has only small and isolated pocket beaches.

There is almost no carbonate material in the beach sands eastward from Punta Cuchara. The beaches are composed of igneous rock fragments, magnetite, and dark monomineralic components with minor amounts of quartz and feldspar.

The beach at Punta Cuchara is being rapidly eroded and a large amount of the land behind the beach has been removed. The low beach to the east, Playa de Ponce, is a free sand removal area and a garbage and junk dump site. It is one of the worst looking stretches of coastline in Puerto Rico (fig. 124). From Punta Carenero east to Punta Petrona, there is almost continuous beach plain interrupted by mangrove, eroding alluvial plain, and rock riprap (fig. 125). More than fifty percent of this coast is suffering severe erosion. The materials range from sand to gravel and are dominantly dark minerals and rock fragments. Several of the beaches have especially high concentrations of magnetite.

The coastline from Jauca to Playa Salinas is a combination of beach plain and mangrove. East of Salinas there is considerable mangrove coast. The Cayos Caribe are small mangrove islands that are behind a fringing reef coastline. From Las Mareas eastward the coast is do-

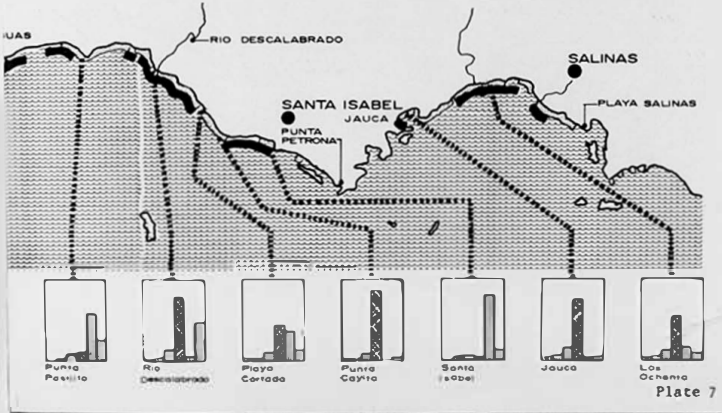



Plate 7

Fig. 125. The lines of accreting beach at Punta Caballon show that in the past the land area has been increasing by the deposition of successive beach lines.

Fig. 126. Jueyes Beach. There is rapid erosion of the beach with undercutting and loss of palm trees from the shoreline. The beach materials are gravel with sand.

Fig. 127. Las Ochenta. The beach is coarse cobble and erosion has been so severe that most of the riprap protection has been replaced with cemented sea wall.

minantly the result of wave erosion of the relatively unconsolidated alluvial plain material that lies south of the central mountains (fig. 126). There is extensive development of narrow beaches at the base of wave cut cliffs. From Arroyo eastward, the coastline is dominantly beach plain (fig. 127).

The beach materials are fragments of igneous rock material with magnetite, dark minerals, and some quartz and feldspar. There is considerable increase in the amount of quartz and feldspar east of Las Mareas and the beach at the mouth of Rio Manuabo is almost entirely quartz and feldspar composition. There is very little calcium carbonate material except at Libre Florida.

Much of the beach material in this part of the Island is gravel sized. The gravel appears to be residual alluvial plain material left in the surf zone as the alluvial plain is cut back by wave action on many of the beaches.

There is severe erosion over almost one-third of the coastline shown on this plate (figs. 128 and 129). Only the mangrove area surrounding Bahia de Jobos and the beaches off Patillas and Rio Maunabo are not showing some signs of severe erosion. The coast from Las Mareas west to Escuela Pozuelo is one of the most severe areas of erosion encountered on the Island (figs. 130 and 131).

The coastline from Punta Tuna to Naguabo is an alternation of rocky headlands that have been partly shaped by marine erosion and valleys of alluvial material that have been worked on by wave action and marine deposition to form broad beach plains (figs. 132 and 133). North of Punta Lima the coastline is mangrove coast, rocky headlands,

## MINERAL COMPOSITION

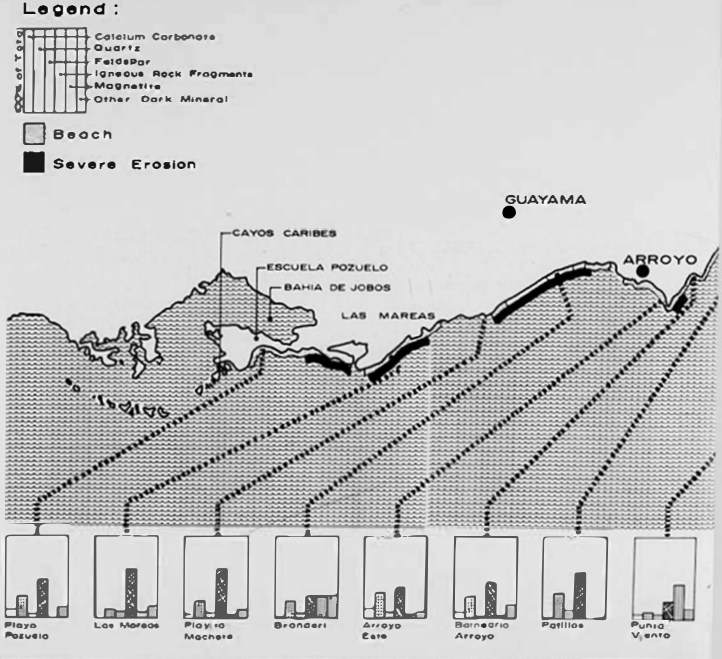


Fig.128. Jobos. Rapid erosion of the shoreline has resulted in a maze of palm trees lying in the water. An extremely large area of former mangrove has been killed

Fig. 129. Las Mareas west. Erosion is equally severe east and west of the jetty that protects the harbor entrance from the dominant westward longshore drift.

Fig. 130. Arroyo west. There is relatively rapid recession of the unconsolidated alluvial plain material and a narrow beach of gravel and sand at the base of the cliff.

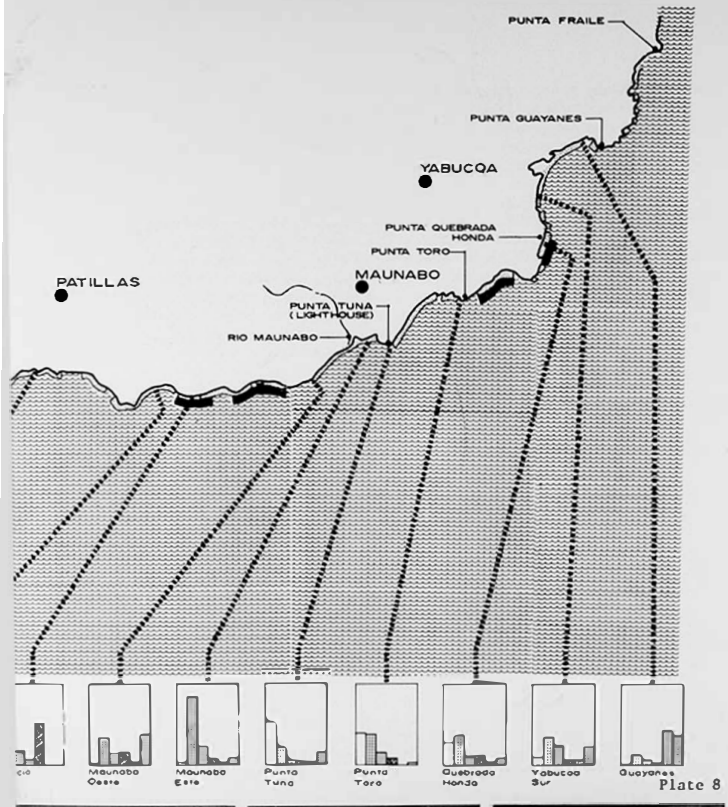






Plate 8

Fig. 131. The undercutting and erosion has not only cut stands of palm trees, but has also undermined the public school at Las Mareas so that it has been abandoned.

Fig. 132. One of the most scenic points on a drive around the coast of Puerto Rico is Cabo Mala Pascua However, there is a widened area of the road for garbage trucks to dump their load.

Fig. 133. Maunabo. There is a wide beautiful beach at the mouth of the Maunabo River. The sands are quartz with some feldspar and igneous rock materials.

and a few small beach plains and pocket beaches.
The eastern end of the island is bordered by a shallow shelf with abundant coral and marine organisms forming carbonate sands. As a consequence the beaches are a mixture of calcium carbonate grains from offshore and quartz and feldspar and igneous rock material and dark minerals from the land area.

Although the composition of the beaches is similar, physical boundaries formed by rocky headlands divide the coast into eight distinct beaches. There may be limited transfer of sand from one beach to another in the offshore zone, but they are distinctly separated physically.

Punta Tuna beach is a beautiful coarse carbonate sand beach with some quartz and igneous rock material that lies east of the Punta Tuna lighthouse (fig. 134). The land adjacent to the beach is pasture for large herds of cattle, but the owners have provided access to the beach.

Punta Toro beach is quartz and carbonate with some feldspar (fig. 135). The quartz and feldspar is derived from the plutonic outcrops north of the beach.

From Quebrada Honda to Guayanes there is a series of pocket beaches and some relatively long stretches of wide beach (fig. 136) composed of quartz and feldspar, with some carbonate and igneous rock material. Guayanes beach, at the north end of this system is especially rich in magnetite (fig. 137). The transport of sand in this system is now interrupted by the deep channel and jetties constructed as part of the Yabucoa Harbor.

The Candelero beach system starts with a group of small pocket

Fig. 134. Punta Tuna. There is a wide and beautiful beach of carbonate and quartz sand east of the rocky promontory of Punta Tuna.

Fig. 135. El Toro Beach. In contrast to Punta Tuna the sands are terrigenous.

Fig. 136 Yabucoa Beach. This is a wide and low beach composed of quartz and feldspar dominantly. There is easy access and facilities for public use.

Fig. 137. Punta Guayanes. There are beautiful small pocket beaches in the rocky headlands that separate Playa de Guayanes from the beaches at Palmas del Mar. The land area is being extensively developed for homes.

beaches between Punta Guayanes and Punta Fraile. There is a continuous beach plain from the Palmas del Mar marina at Punta Fraile to Morro de Humacao (fig. 138). The composition is dominantly calcium carbonate. There is severe erosion at Punta Candelero and for a short distance north.

The Morillo beach is quartz with some igneous rock fragments and dark minerals (fig. 139). From here northward, the beach sands are dominantly terrigenous origin. The beach from El Morillo to Naguabo is a relatively broad beach of quartz and feldspar with some dark minerals and igneous rock material. There is severe erosion along the northern half of this beach and extensive rip-rap has been emplaced to protect the highway (fig. 140). Naguabo beach is adjacent but slightly separated from the rest of the beach. The calcium carbonate content is much higher in this beach.

Fig. 138 Palmas del Mar. The beach and coastline was extensively re-shaped as part of the Palmas del Mar development. The beach sand is principally carbonate.

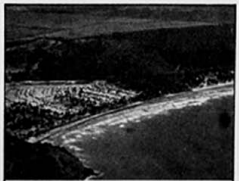


Fig. 139. El Morrillo. There is a wide quartz-feldspar beach north of the headland at El Morrillo.

Fig. 140. Playa de Humacao north. There is extensive erosion of the beach from Playa de Humacao to Rio Blanco.

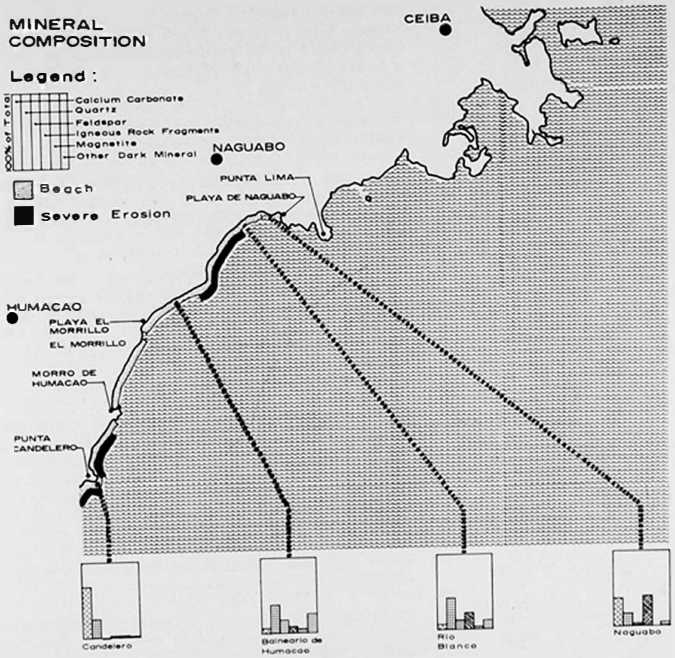

MINERAL
COMPOSITION
Legend :
100% of Total
Calcium Carbonate
Quartz
Feldspar
Igneous Rock Fragments
Magnetite
Other Dark Mineral
Beach
Severe Erosion
CEIBA
NAGUABO
PUNTA LIMA
PLAYA DE NAGUABO
HUMACAO
PLAYA EL MORRILLO
EL MORRILLO
MORRO DE HUMACAO
PUNTA CANDELERO
Candelero
Balneario de Humacao
Rio Blanco
Naguabo

Plate 9

SUMMARY AND RECOMMENDATIONS

1. The beach system of Puerto Rico is not continuous, but is broken into separate beach systems. From preliminary data, there seems to be transport from one beach to another within a beach system, but little or no communication between separate systems.

   The termination of a beach system is generally a rocky headland with relatively deep water adjacent to the shore.

2. Since the communication from system to system is probably minimal, modifications of the shoreline within a particular beach sould have an effect only on other beaches within the same system.

3. Erosion of the shoreline in general and beaches in particular is a common phenomenon. Accretion of the shoreline is generally occuring only in areas of mangrove shoreline.

4. The mangrove is a major factor limiting erosion. Where mangrove forests have been replaced by coconut groves erosion has generally been initiated.

5. Erosion is proceding at a much more rapid rate where the shoreline is unconsolidated or poorly consolidated alluvial sediments.

6. Erosion is much more severe where offshore coral reefs and beach rock or submerged eolianite has been breached and reduced in size.

7. Where sand has been removed from the dune system, major erosion seems to be eminent.

8. The removal of littoral transported sand from river mouths has resulted in accelerated erosion. This is an area in which control of sand extraction is of major importance.

9. Man's activities of a wide variety, from agriculture and urbanization to harbor and industrial construction, has adversely affected reef areas and resulted in increased erosion.

10. Addition of riprap has given protection to local areas, but has also shifted the locus of erosion and caused problems in other areas.

11. Removal of mangrove along the shoreline has resulted in increased erosion.

12. It is possible that sand could be removed at the downstream end of a beach system without an adverse effect on the environment. i.e. La Plata River, Guanajibo River, Punta

Ventana Canyon, Malecon dock areas. The rate and extent of removal would have to be controlled to avoid environmental complications.

13. A major prospect for sand resources is the submerged sand bodies on the insular shelf of Puerto Rico.

14. The main conflict of interest in the beach portion of the coastal zone is between those activities which would use the beach area i.e. recreation, tourism, urbanization, industrial sites and the construction materials industry which would remove major amounts of beach material.

    Secondary conflicts exist between the users of the beach in terms of natural quality of the environment. The solution of these conflicts is a matter of planning and zoning.

15. To date we have had limited data for use in planning the utilization of the beach areas. A major task in collecting and analyzing data so that we will have a major body of information with which planning decisions can be made.

16. The program to date has been collection of preliminary and relatively unsophisticated data for the preparation of a general interest publication. The major aim is to inform and alert private citizens and government officials of the potential problems and the need for careful utilization of our beach resources.

17. On the basis of the data analyzed to date, specific recommendations can be made as to areas where river and dune dredging, and near shore dredging should not be allowed. Where there is a requirement to keep the bar of a river open, and removal of the material from the system is causing accelerated erosion, the dredged sand should be returned to the system downstream.

    Tentative areas of non-harmful sand extraction can also be suggested. In these areas, the beach equilibrium should be monitor before and during any dredging operations.

18. The continuation of the beach study program should include:

    measurement of beach profiles in selected areas to establish the equilibrium beach situation

    measurement of currents and current systems in the nearshore zone

    measurement of the rates of movement of the beach sand alongahore in selected areas

    detailed studies of the rate of erosion in areas of severe erosion as outlined in this study

location of any evaluation of offshore sand bodies. This should include surface sampling, coring, and seismic surveys to determine potential volumes of available sand.

continued studies of the characteristics (grain size, composition, construction properties, etc.) of both offshore and beach deposits.

19. There should be consideration of legislation and grant procedures that would encourage the developing of offshore sand extraction.

20. Control of dune, river, beach and very nearshore dredging and construction should be developed by new legislation or implementation of existing laws. Patterns for this can be found in Florida, California, and other coastal states of the United States.

A C K N O W L E D G E M E N T

| | |
|---|---|
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| Sample cuts and discussion | James Trumbull |
| Report Preparation | Staff of the Puerto Rico Coastal Zone Management Program |